Computed Pion Yields from a Tantalum Rod Target

Comparing MARS15 and GEANT4 across proton energies

Stephen Brooks, Kenny Walaron
Scoping Study meeting, September 2005

Proton Driver Energy and Pulse Structure Implications

(An overall context)

Stephen Brooks
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Proton Source Parameters

I. Proton energy

II. Bunch length

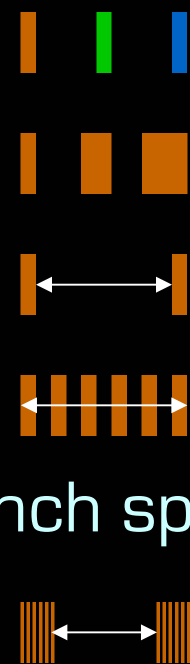
III. Bunch spacing

IV. Pulse length

= Number of bunches × bunch spacing

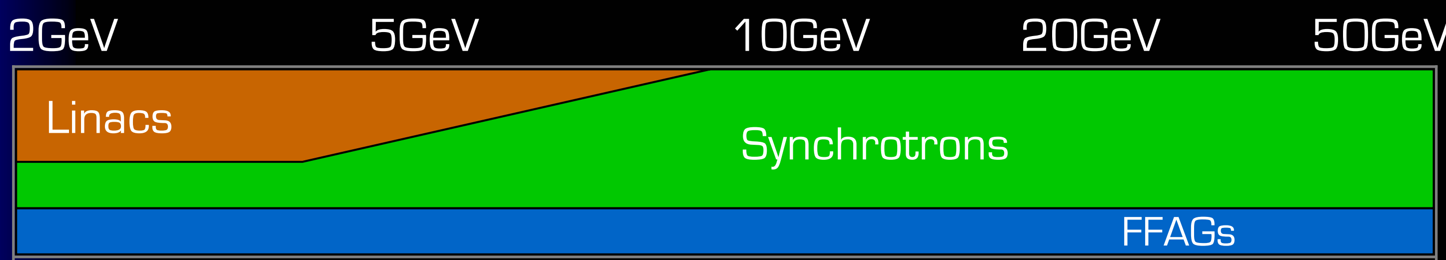
V. Pulse spacing

= 1/(Rep. rate)

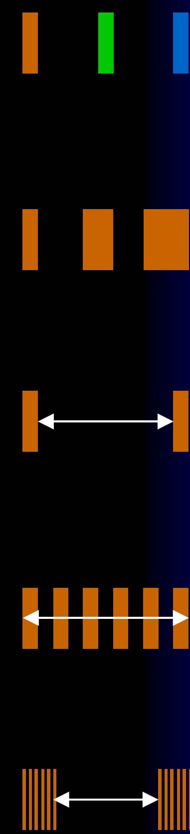


Assume 4-5MW fixed mean beam power.

Upstream Correlations

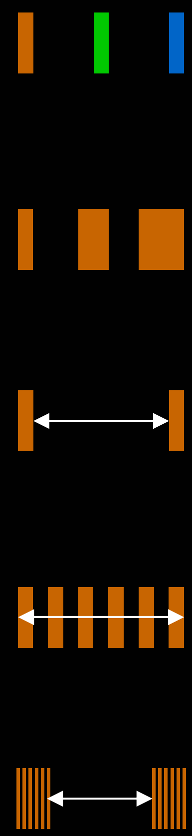


RF voltage in bunch compression ring vs. space charge	
Bunching ring RF frequency, bucket filling pattern	…or separate extraction strategy
Bunching ring circumference minus extraction gap	
Repetition rate of linac or slowest synchrotron (possibly doubled up)	



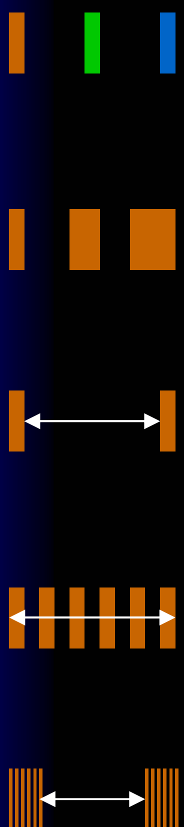
Target Issues

Solids	Liquids
Energy deposition minimal around 8GeV	Similar?
Time scale too short to have an effect	
Sufficient spacing can split up thermal shocks	“Pump-probe” effects due to liquid cavitation may appear on this timescale
…so shock is divided by the number of bunches	
Low rep. rate means a larger shock each time	Faster rep. rate needs a high jet velocity



Downstream Correlations

Capture | Phase rotation | Cooling | Acceleration | Storage ring



- Pion momentum range increases with energy, becomes more difficult to capture
- Long bunches increase longitudinal emittance, phase rotation becomes harder
- Avoid 'traffic jams' in the longer-duration rings (or provide sufficient circumference)
- If bunches stored behind each other in storage ring, need enough circumference
- Low rep. rate means high peak beam loading; difficult to charge RF cavities

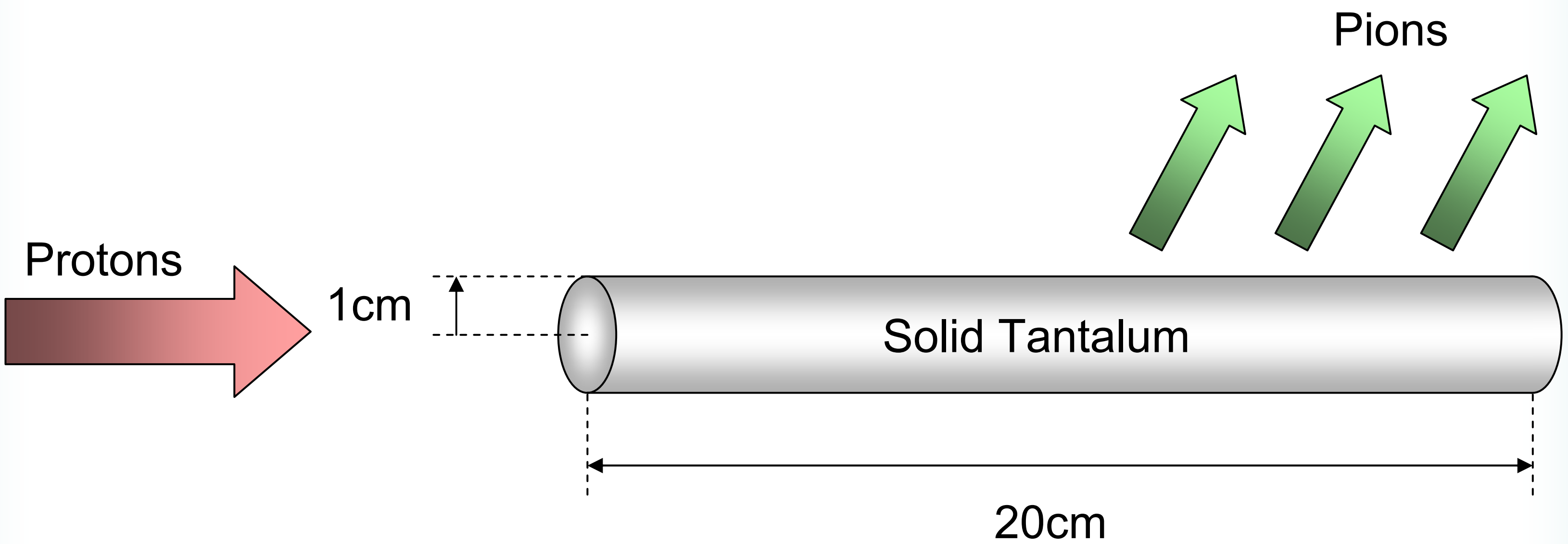
Scoping Study and Beyond…

- There are a lot of interactions going on
  - Can we really do this in our heads?
  - Perhaps they should be tabulated somewhere
- There are a lot of parameters
  - How do we run all possibilities… automation?
- There are a lot of constraints
  - Can we handle this systematically?
    - Defining “engineerable ranges” would be useful

Contents

- Benchmark problem
- Physics models and energy ranges
  - Effects on raw pion yield and angular spread
- Probability map “cuts” from tracking
  - Used to estimate muon yields for two different front-ends, using both codes, at all energies
- Target energy deposition
- Variation of rod radius (note on tilt, length)

Benchmark Problem

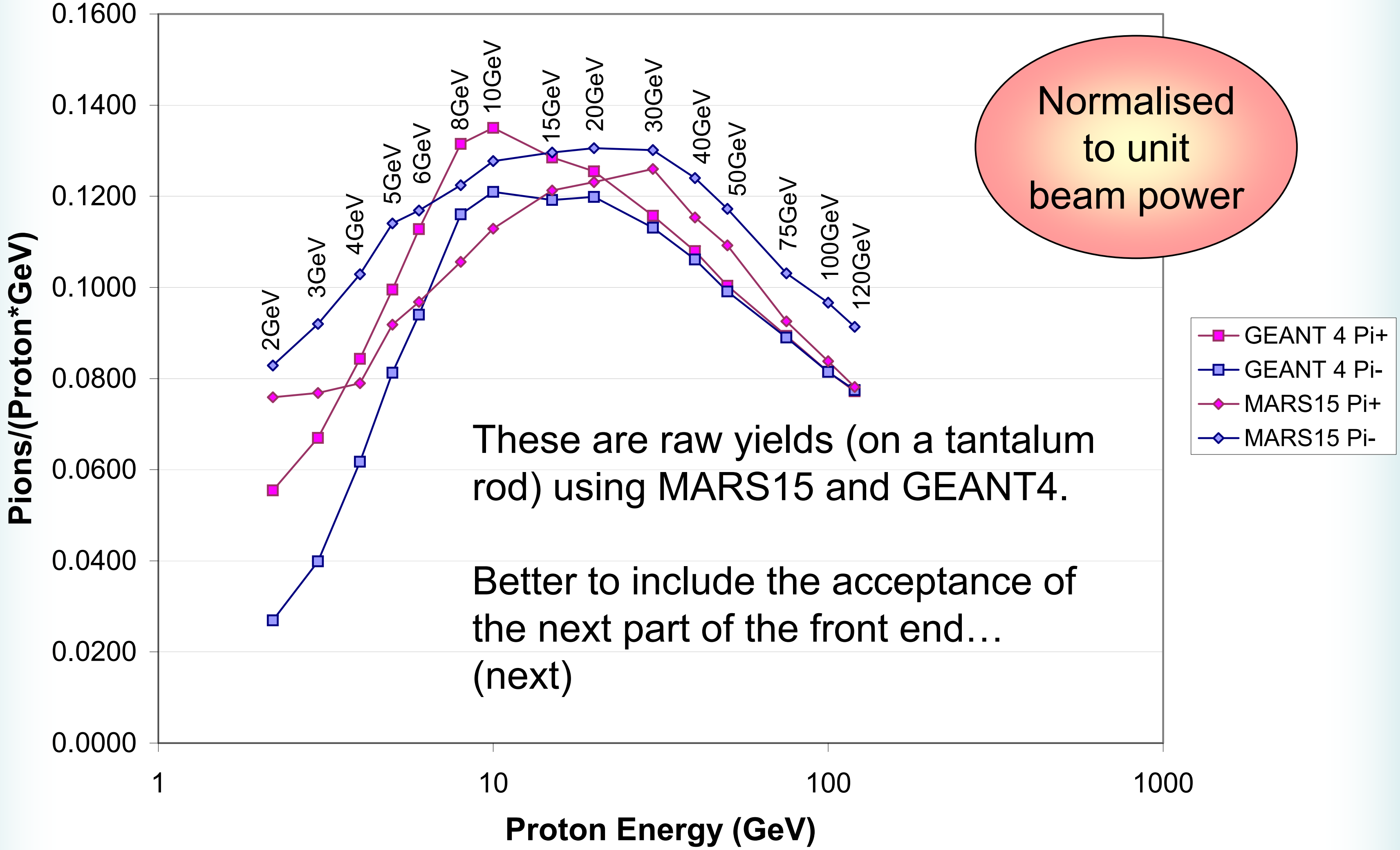


- Pions counted at rod surface
- **B**-field ignored within rod (negligible effect)
- Proton beam assumed parallel
  - Circular parabolic distribution, rod radius

Possible Proton Energies

Proton Driver	GeV	RAL Studies
Old SPL energy	2.2	
	3	5MW ISIS RCS 1
[New SPL energy 3.5GeV]	4	
	5	Green-field synch.
	6	5MW ISIS RCS 2
FNAL linac (driver study 2)	8	RCS 2 low rep. rate
	10	4MW FFAG
[FNAL driver study 1, 16GeV]	15	ISR tunnel synch.
[BNL/AGS upgrade, 24GeV]	20	
JPARC initial	30	PS replacement
JPARC changed their mind?	40	
JPARC final	50	
	75	
	100	
FNAL injector/NuMI	120	

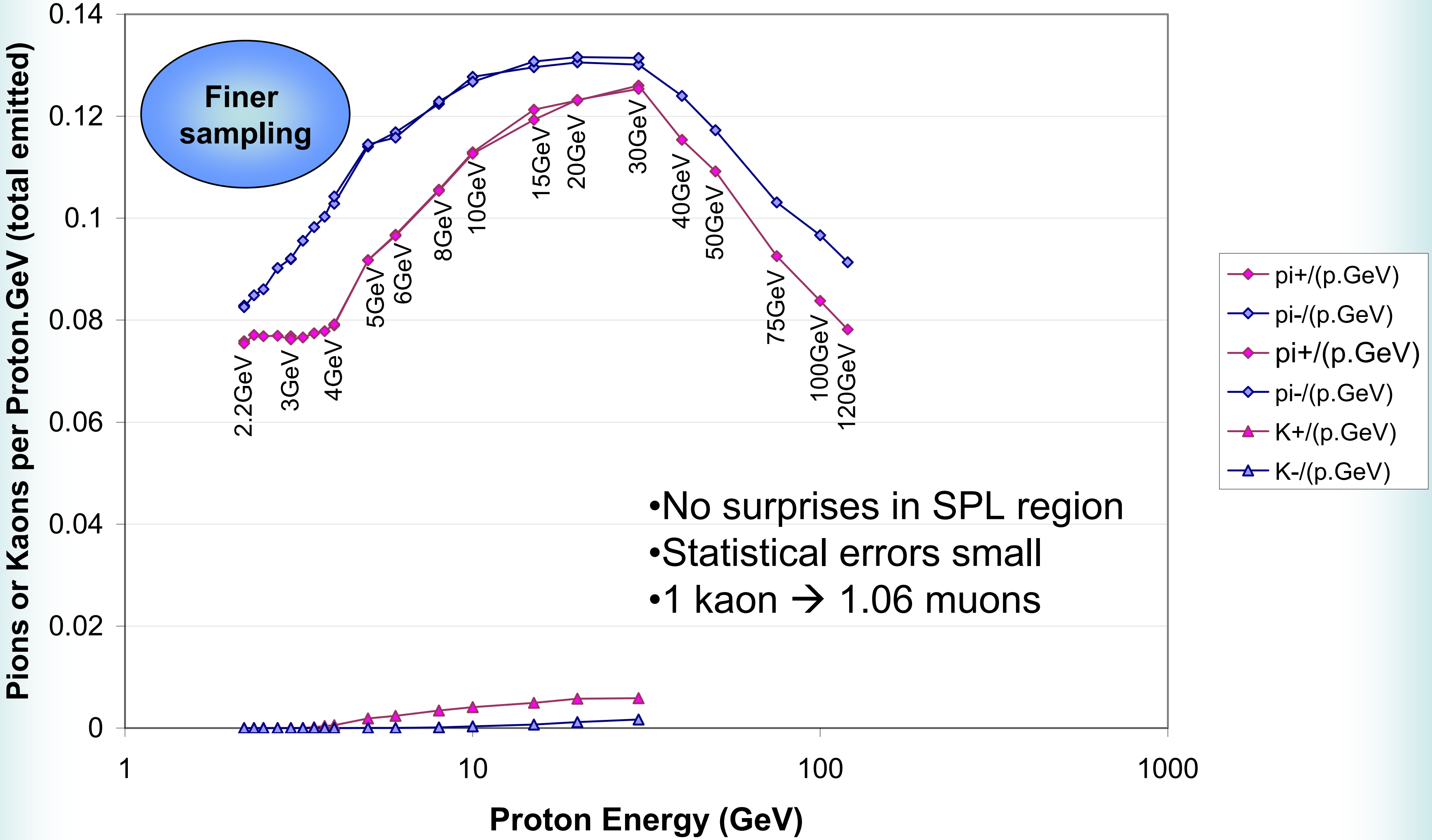
Total Yield of π^+ and π^-



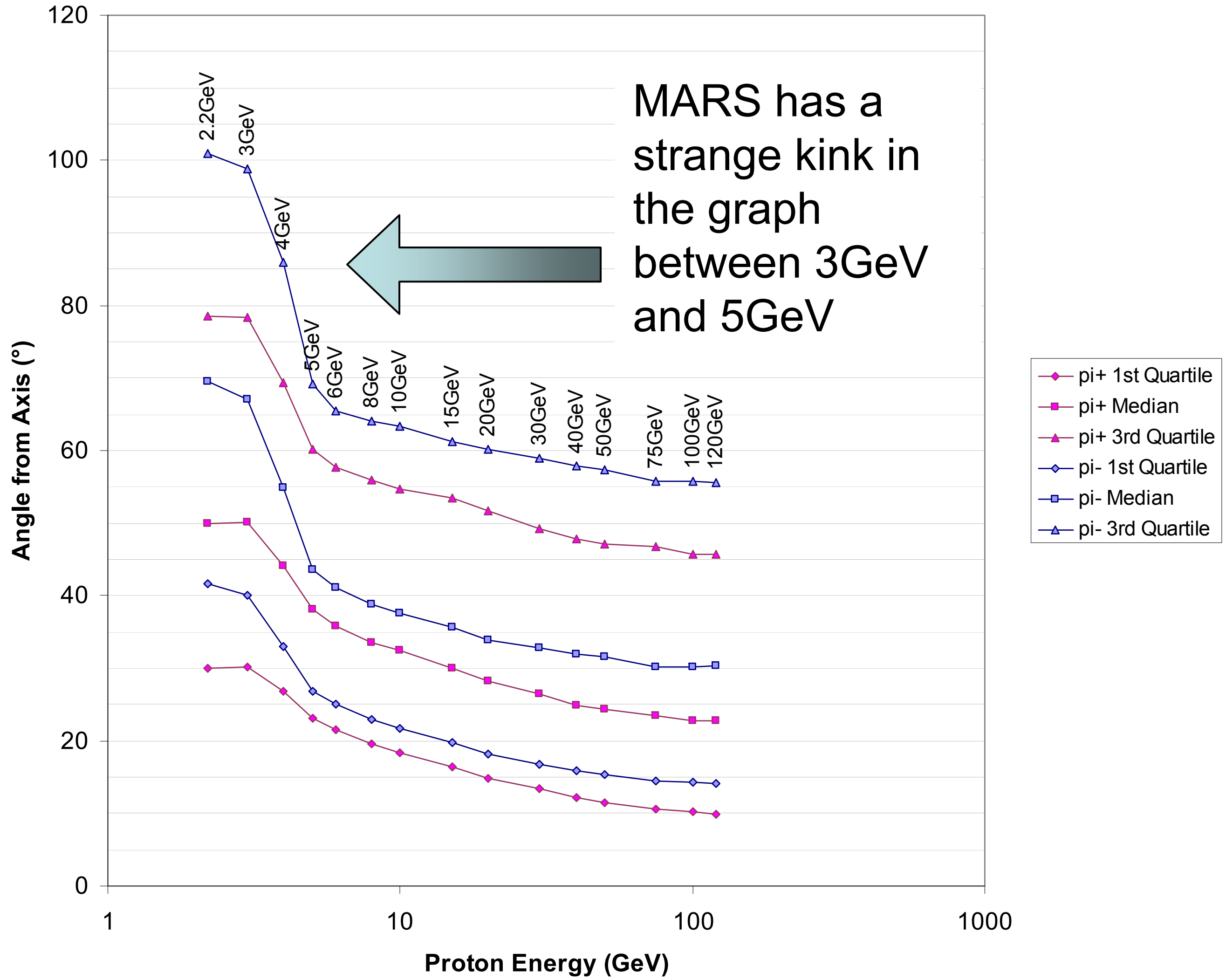
These are raw yields (on a tantalum rod) using MARS15 and GEANT4.

Better to include the acceptance of the next part of the front end… (next)

Yield of $\pi^{\pm}$ and $K^{\pm}$ in MARS



Angular Distribution: MARS15



MARS15 Uses Two Models

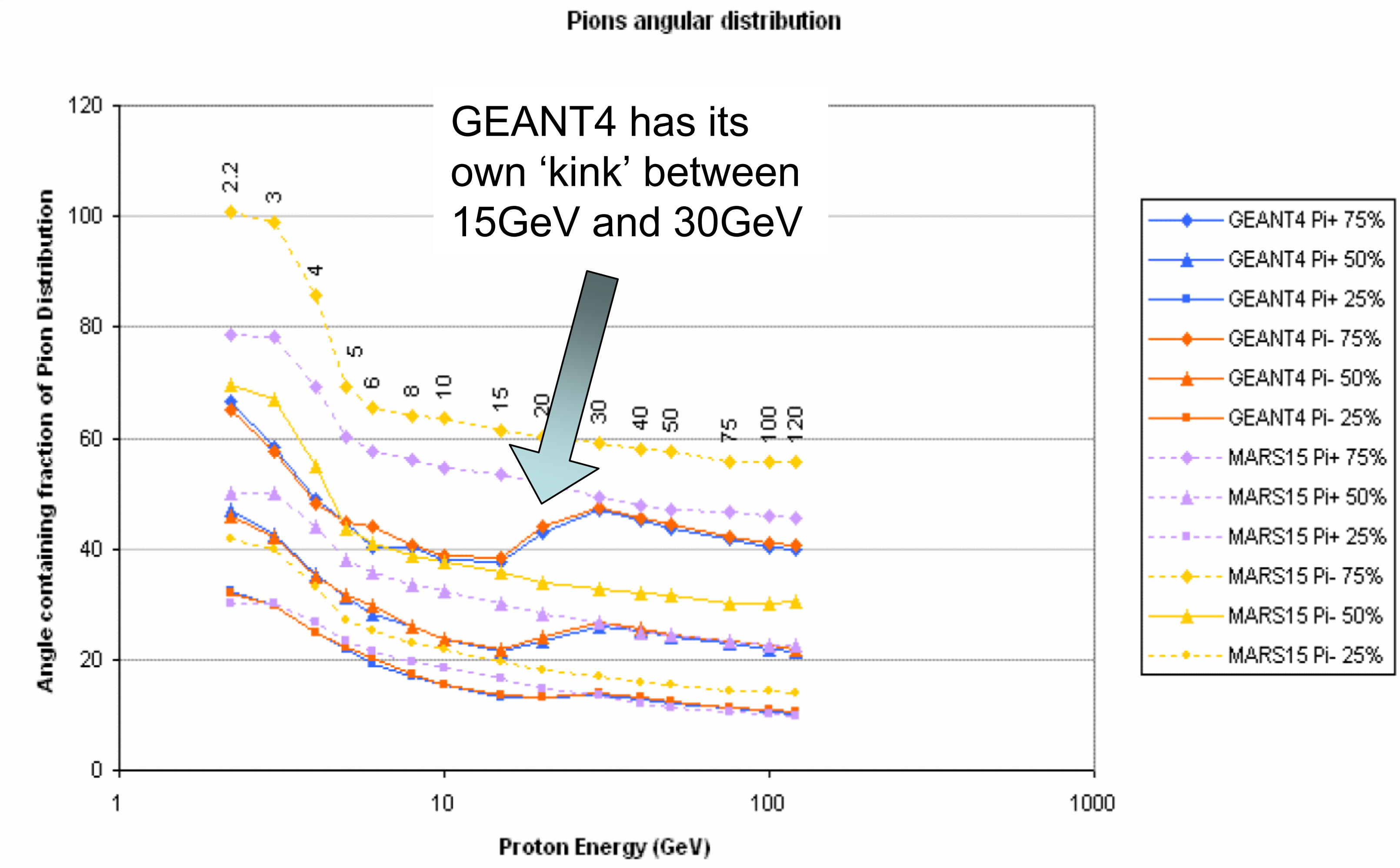
	<3GeV	3-5	>5GeV
MARS15	CEM2003		Inclusive

- The “Cascade-Exciton Model” CEM2003 for E<5GeV
- “Inclusive” hadron production for E>3GeV

Nikolai Mokhov says:

A mix-and-match algorithm is used between 3 and 5 GeV to provide a continuity between the two domains. The high-energy model is used at 5 GeV and above. Certainly, characteristics of interactions are somewhat different in the two models at the same energy.

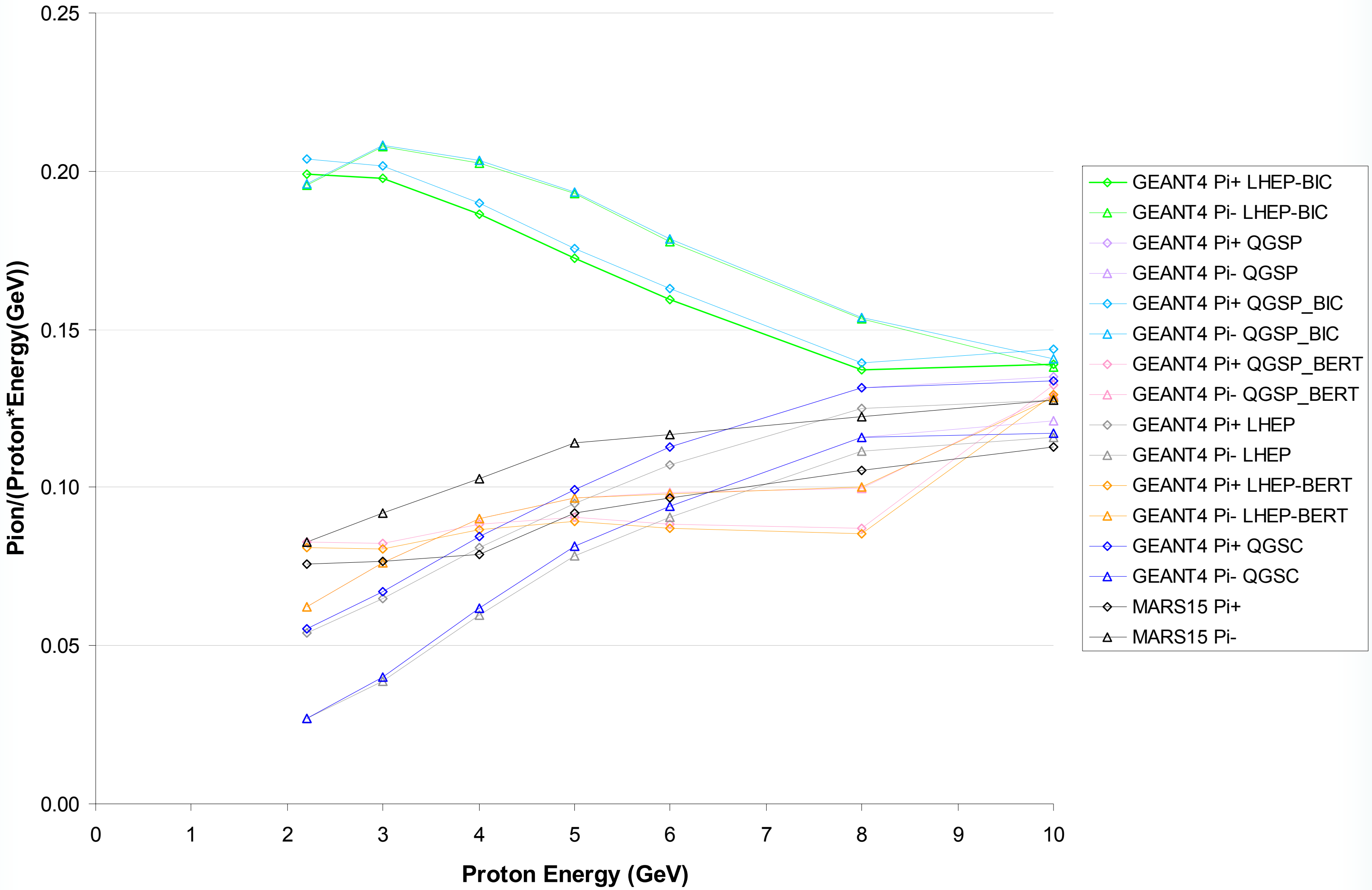
Angular Distribution: +GEANT4



GEANT4 Hadronic “Use Cases”

	<3GeV	3-25GeV	>25GeV
LHEP	GHEISHA inherited from GEANT3		
LHEP-BERT	Bertini cascade		
LHEP-BIC	Binary cascade		
QGSP (default)			Quark-gluon string model
QGSP-BERT			
QGSP-BIC			
QGSC			+ chiral invariance

Total Yield of π^+ and π^-: +GEANT4



Raw Pion Yield Summary

- It appears that an 8-30GeV proton beam:
  - Produces roughly twice the pion yield…
  - …and in a more focussed angular cone

...than the lowest energies.

- **Unless** you believe the BIC model!
- **Also:** the useful yield is crucially dependent on the capture system.

Tracking through Two Designs

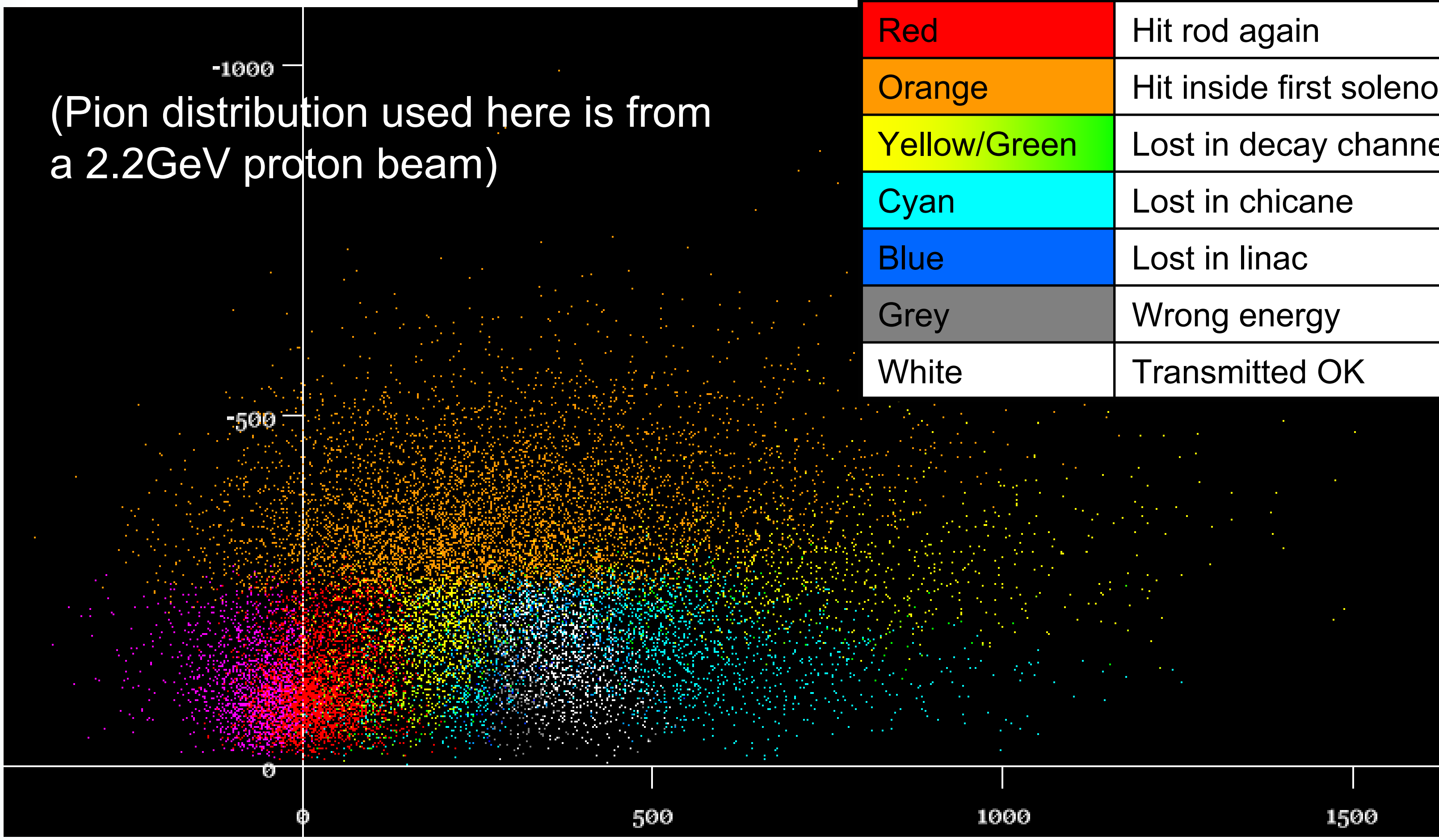
- Both start with a solenoidal channel
- Possible non-cooling front end:
  - Uses a magnetic **chicane** for bunching, followed by a muon **linac** to 400±100MeV
- RF **phase-rotation** system:
  - Line with cavities reduces energy spread to 180±23MeV for injecting into a cooling system

Fate Plots

- Pions from one of the MARS datasets were tracked through the two front-ends and plotted by (p_L, p_T)
  - Coloured according to how they are lost…
  - …or white if they make it through
- This is not entirely deterministic due to pion → muon decays and finite source

Fate Plot for Chicane/Linac

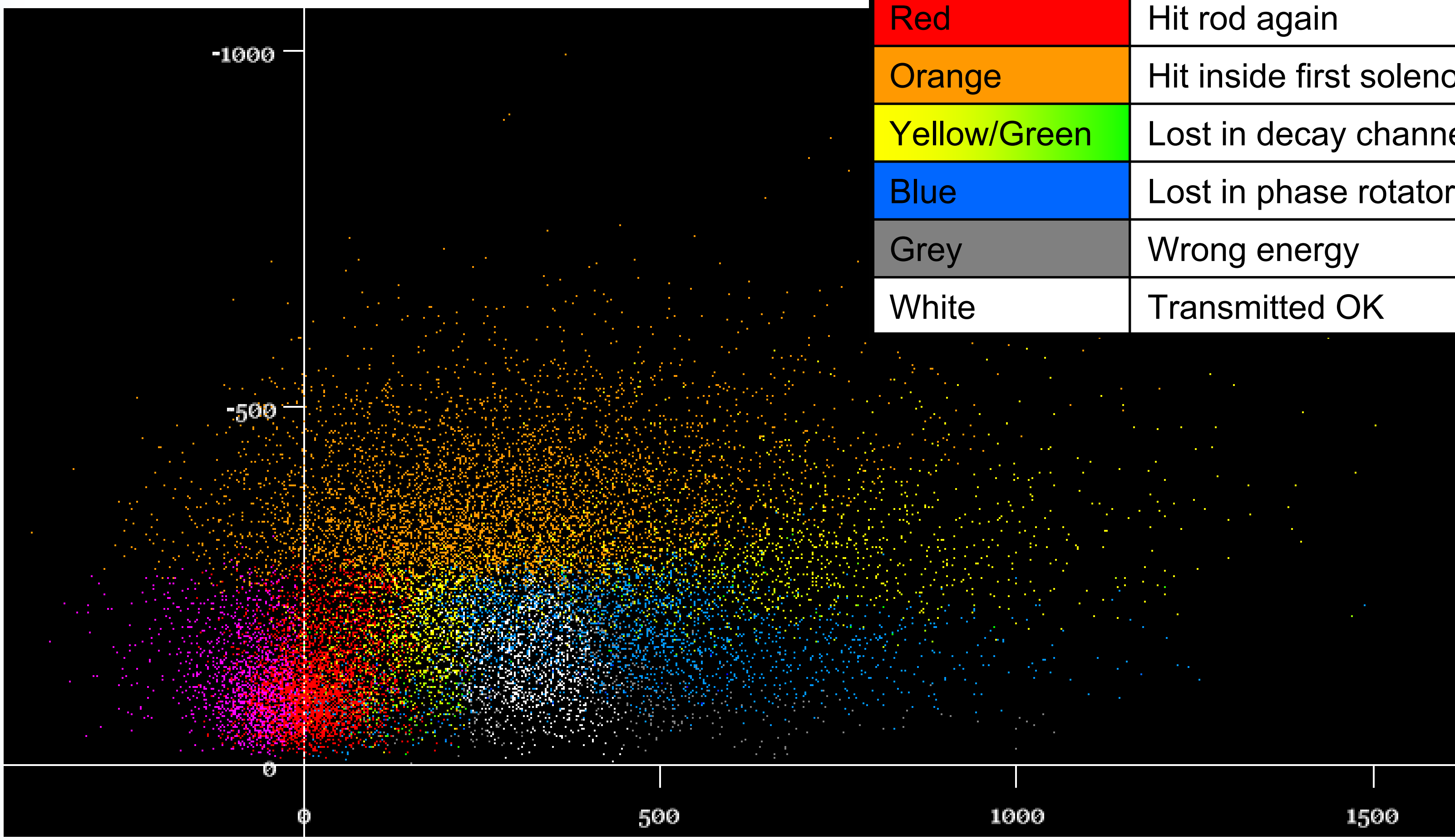
Magenta	Went backwards
Red	Hit rod again
Orange	Hit inside first solenoid
Yellow/Green	Lost in decay channel
Cyan	Lost in chicane
Blue	Lost in linac
Grey	Wrong energy
White	Transmitted OK



(Pion distribution used here is from a 2.2GeV proton beam)

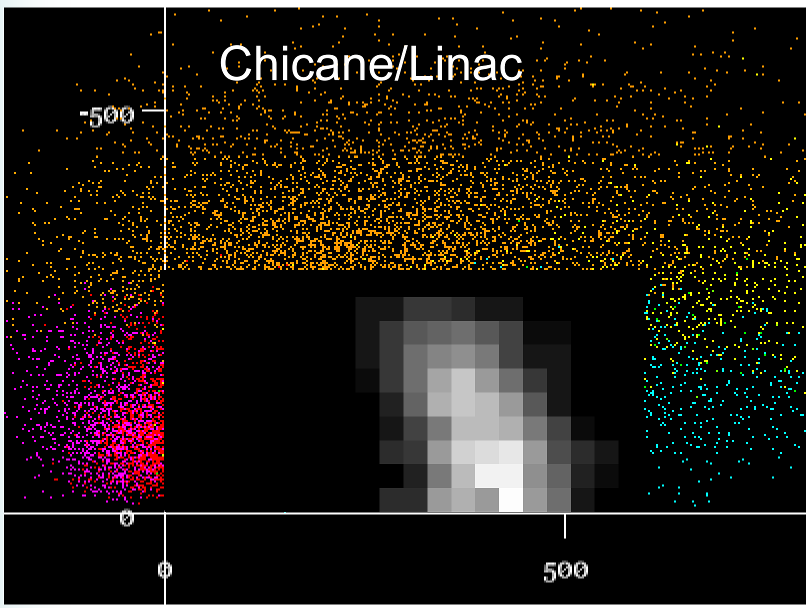
Fate Plot for Phase Rotation

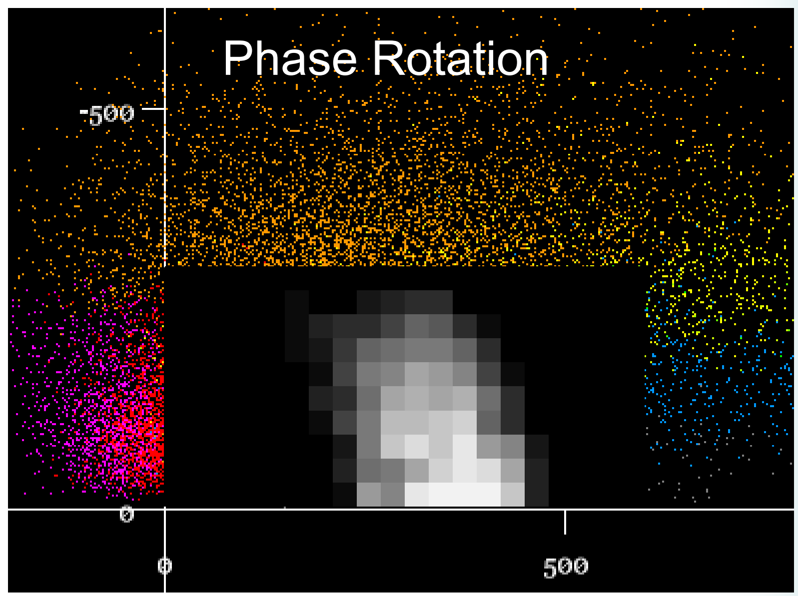
Magenta	Went backwards
Red	Hit rod again
Orange	Hit inside first solenoid
Yellow/Green	Lost in decay channel
Blue	Lost in phase rotator
Grey	Wrong energy
White	Transmitted OK



Probability Grids

- Can bin the plots into 30MeV/c squares and work out the transmission probability within each

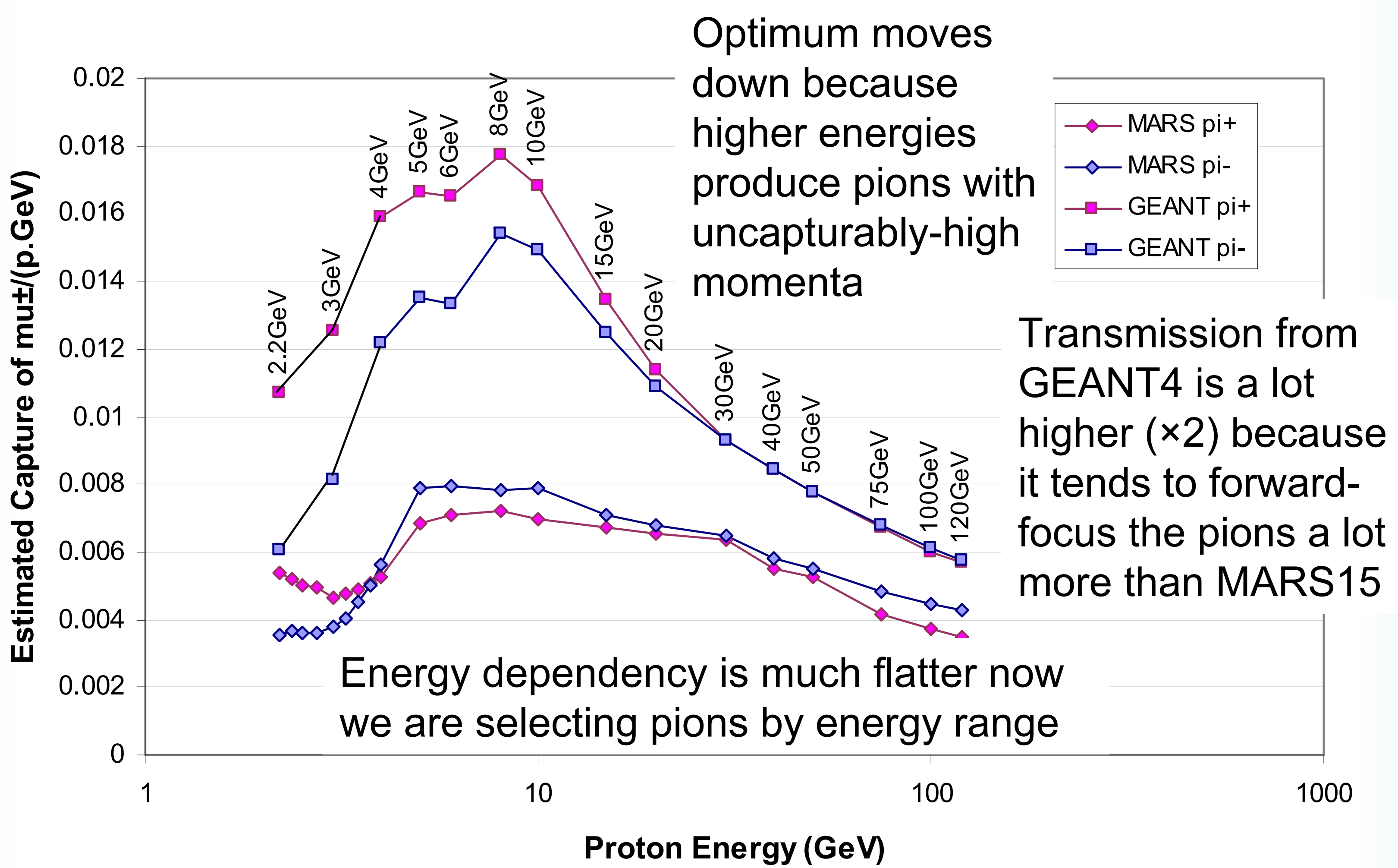




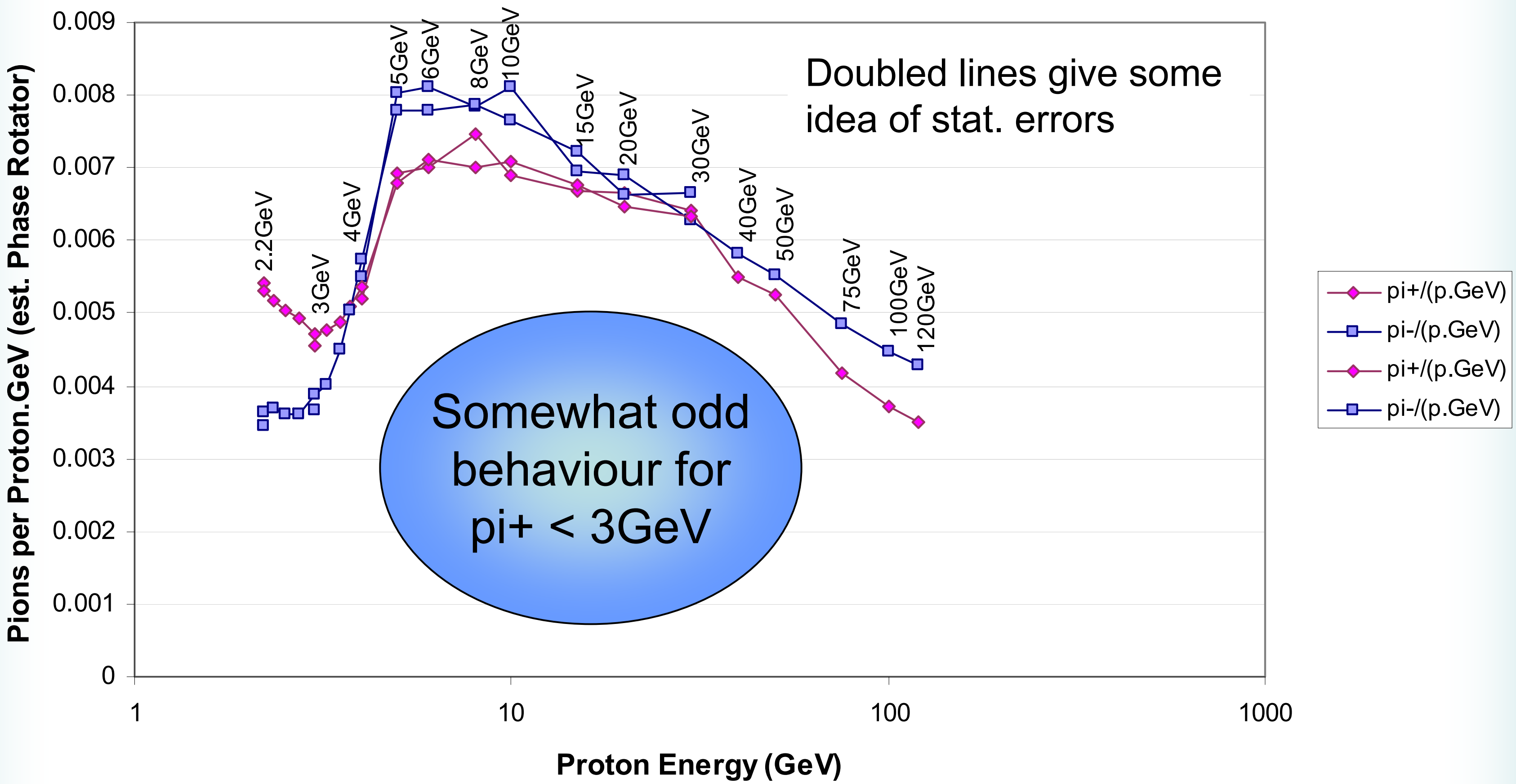
Probability Grids

- Can bin the plots into 30MeV/c squares and work out the transmission probability within each
- These can be used to estimate the transmission quickly for each MARS or GEANT output dataset for each front-end

Phase Rotator Transmission



Phase Rotator Transmission (zooming into MARS15)



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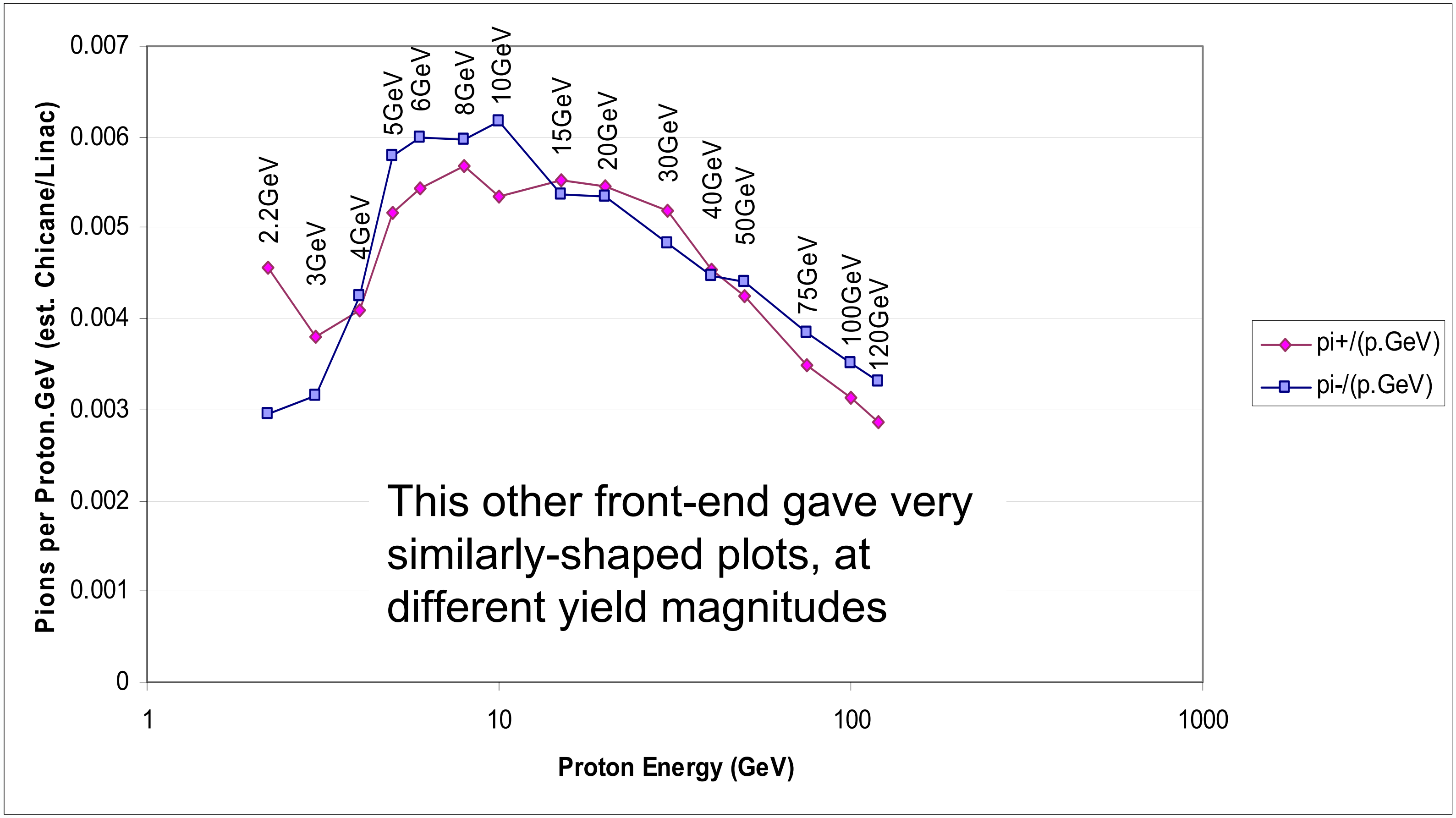
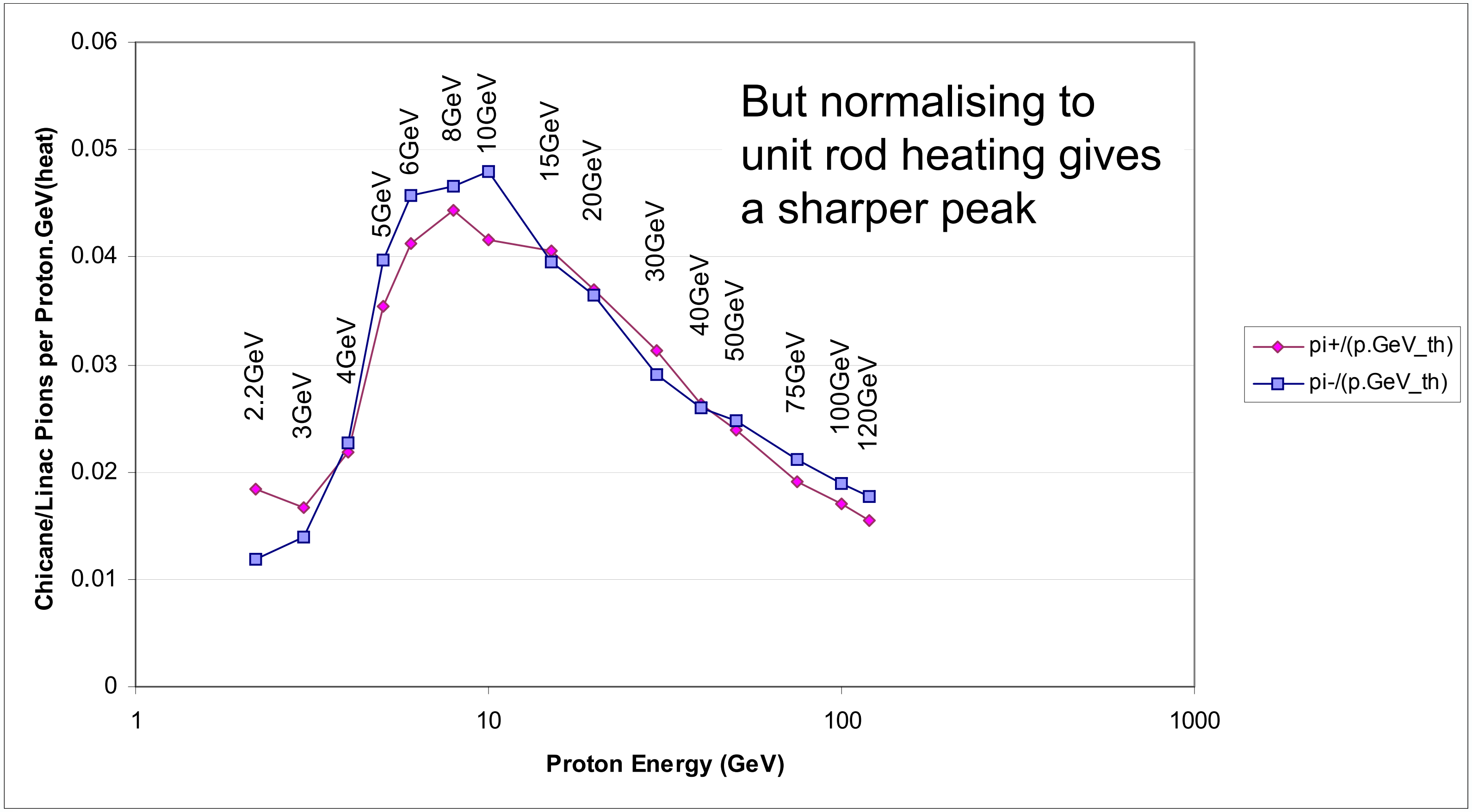
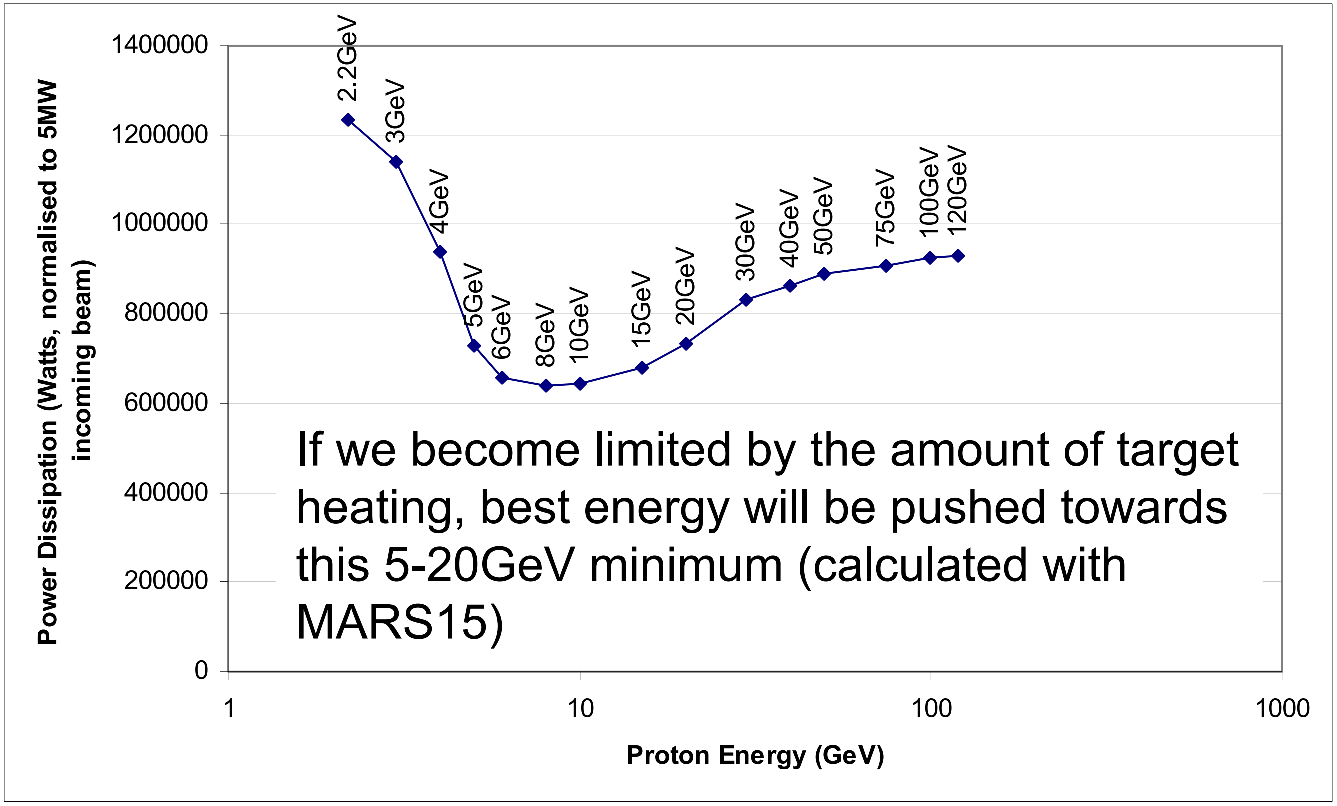
Chicane/Linac Transmission (MARS15)



Chicane/Linac Transmission (MARS15)



Energy (heat) Deposition in Rod



- Scaled for 5MW total beam power; the rest is kinetic energy of secondaries

Variation of Rod Radius

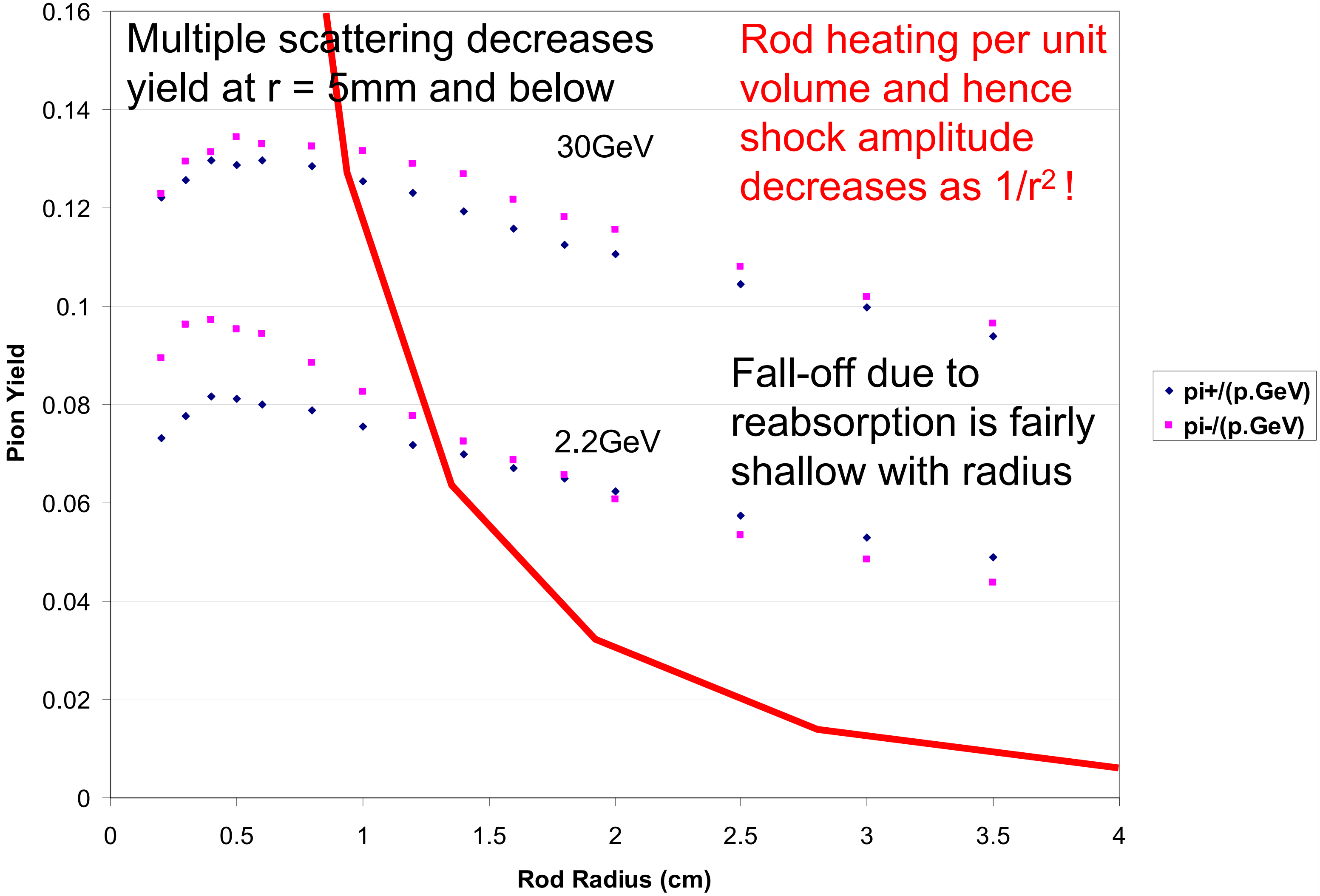
- We will change the incoming beam size with the rod size and observe the yields

Variation of Rod Radius

- We will change the incoming beam size with the rod size and observe the yields
- For larger rods, the increase in transverse emittance may be a problem downstream
- Effective beam-size adds in quadrature to the Larmor radius:

$$r_{eff} = \sqrt{r^2 + \left(\frac{p_T}{eB_z}\right)^2}$$

Total Yield with Rod Radius



Note on Rod Tilt

- All tracking optimisations so far have set the rod tilt to zero
- The only time a non-zero tilt appeared to give better yields was when measuring immediately after the first solenoid
- Theory: tilting the rod gains a few pions at the expense of an increased horizontal emittance (equivalent to a larger rod)

Conclusions – energy choice

- Optimal ranges appear to be:

According to:	For π^+:	For π^-:
MARS15	5-30GeV	5-10GeV
GEANT4	4-10GeV	8-10GeV

Conclusions – codes, data

- GEANT4 'focusses' pions in the forward direction a lot more than MARS15
  - Hence double the yields in the front-ends
- Binary cascade model needs to be reconciled with everything else
- Other models say generally the same thing, but variance is large
  - HARP data will cover 3-15GeV, but when?

Conclusions – other parameters

- A larger rod radius is a shallow tradeoff in pion yield but would make solid targets much easier
- Tilting the rod could be a red herring
  - Especially if reabsorption is not as bad as we think
- So making the rod coaxial and longer is possible

Future Work

- Different rod materials (C, Ni, Hg) for scoping study integration
  - Length varied with interaction length
- Replace probability grids by real tracking
  - Also probes longitudinal phase-space effects, e.g. from rod length
- Extend energies to below 2.2GeV to investigate MARS 'kink', if physical!

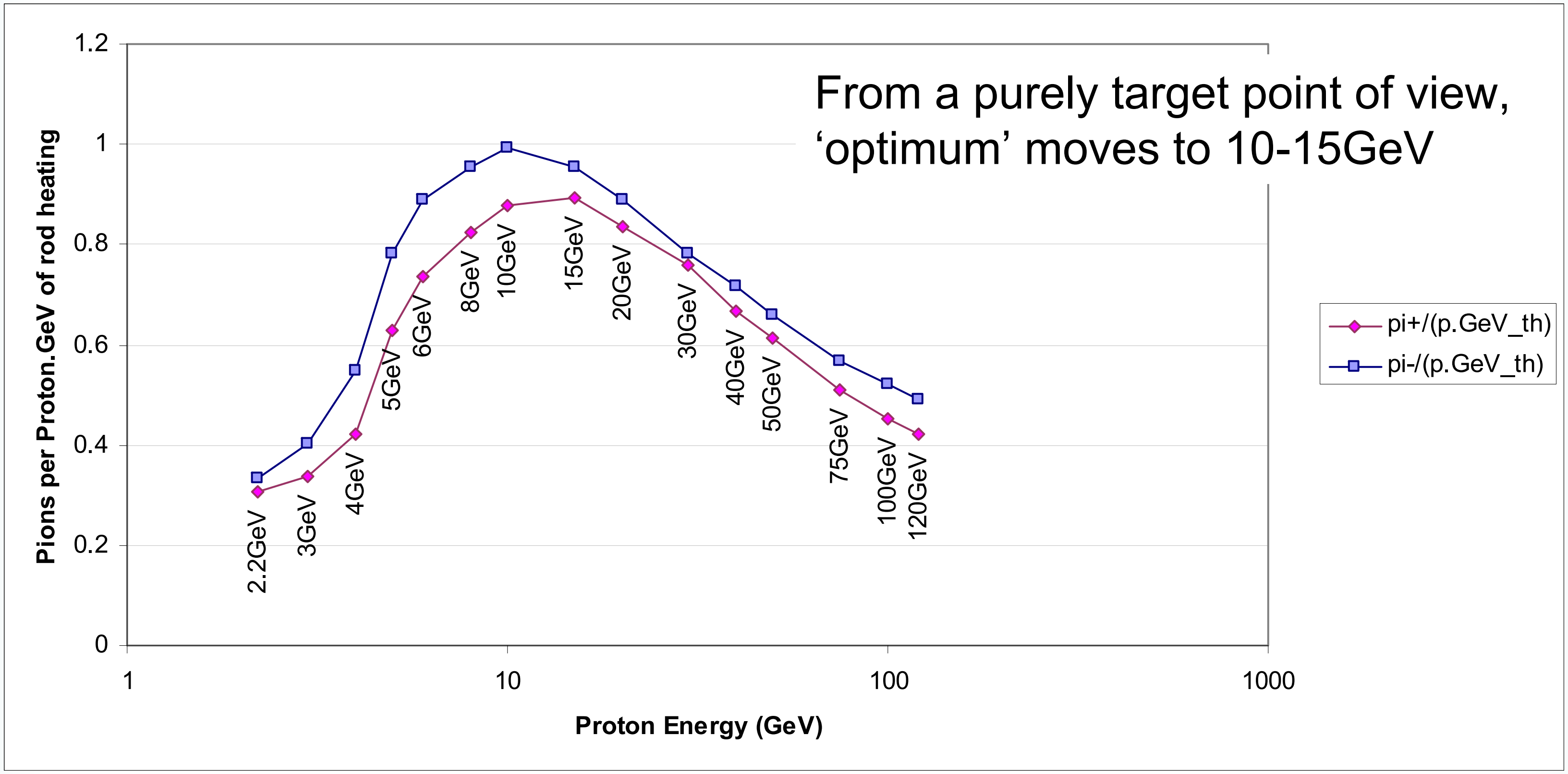
References

- S.J. Brooks, Talk given at NuFact'05: *Comparing Pion Production in MARS15 and GEANT4*; http://stephenbrooks.org/ral/report/

- K.A. Walaron, **UKNF Note 30**: *Simulations of Pion Production in a Tantalum Rod Target using GEANT4 with comparison to MARS*; http://hepunx.rl.ac.uk/uknf/wp3/uknfnote_30.pdf

Now updated

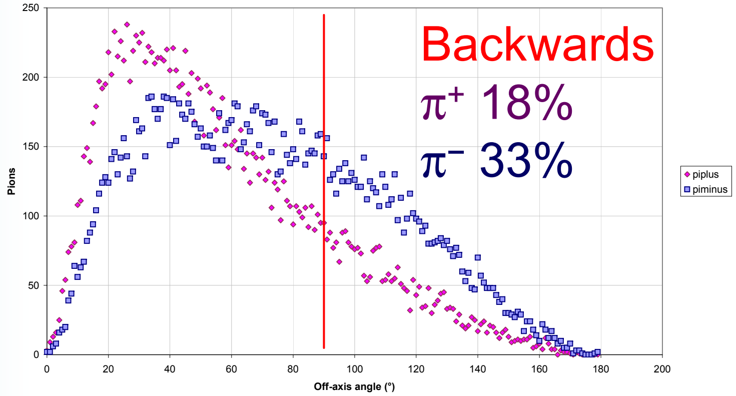
Total Yield of π^+ and π^-



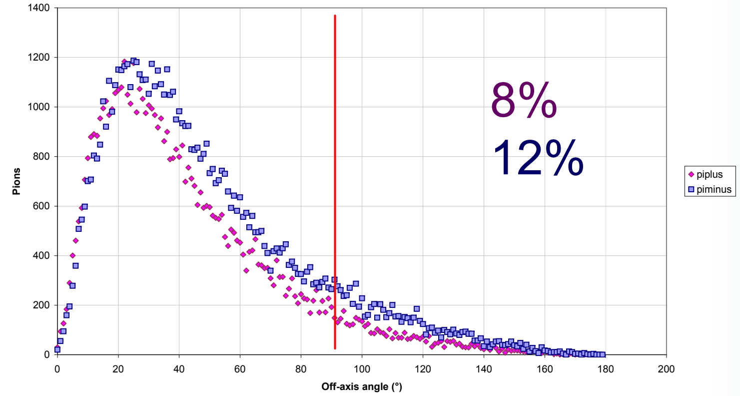
- Normalised to unit rod heating (p.GeV = 1.6×10^{-10} J)

Angular Distribution

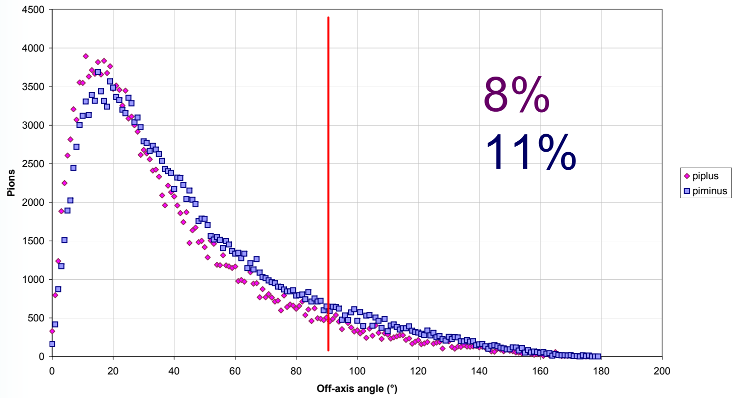
2.2GeV



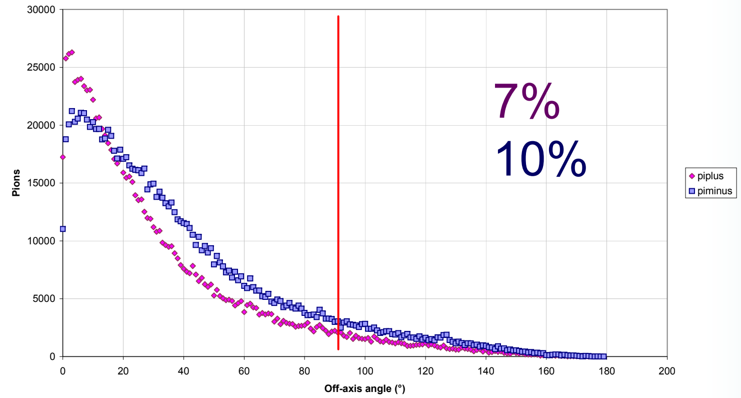
6GeV



15GeV



120GeV



Possible Remedies

- Ideally, we would want **HARP data** to fill in this “gap” between the two models
- K. Walaron at RAL is also working on benchmarking these calculations against a GEANT4-based simulation
- Activating LAQGSM is another option
- We shall treat the results as ‘roughly correct’ for now, though the kink may not be as sharp as MARS shows

Simple Cuts

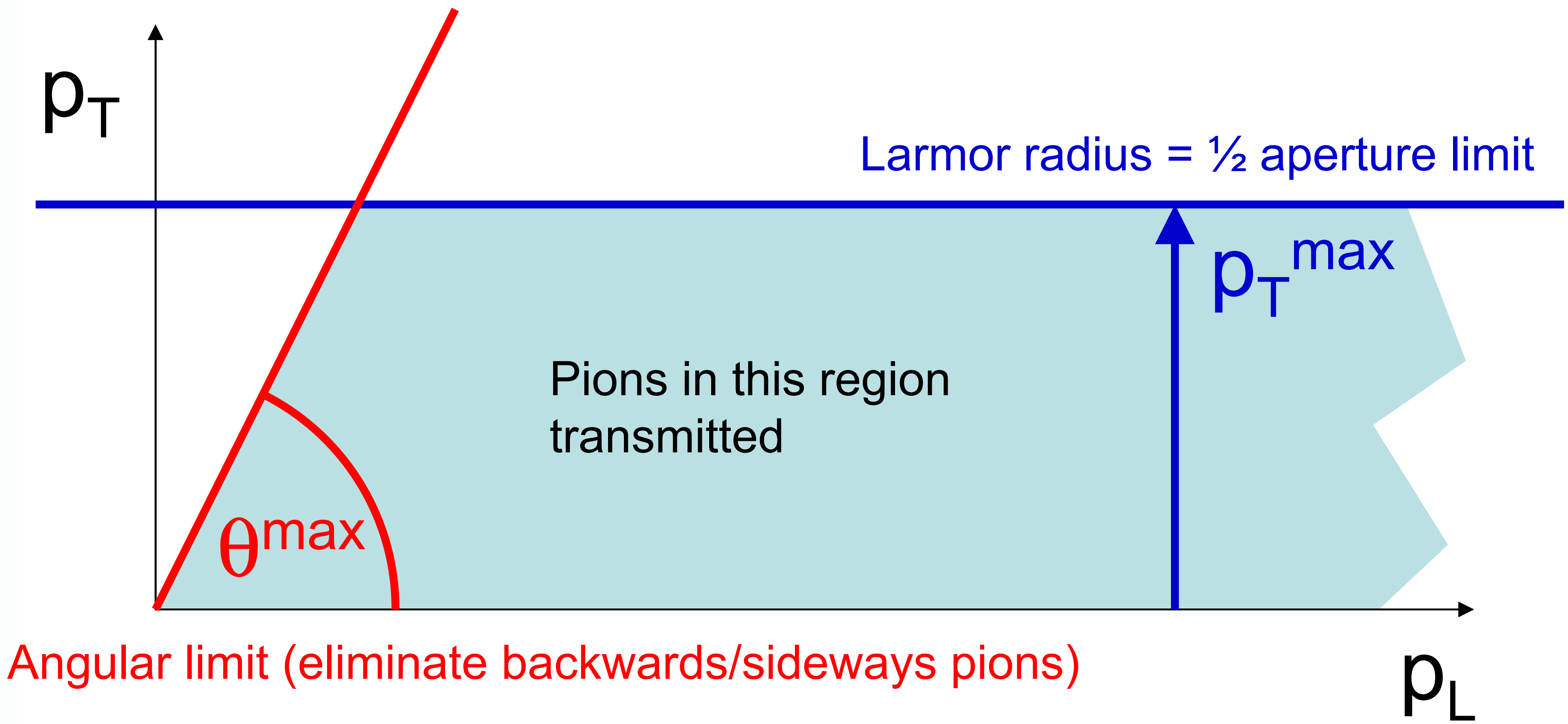
- It turns out geometric angle is a badly-normalised measure of beam divergence
- Transverse momentum and the magnetic field dictate the Larmor radius in the solenoidal decay channel:

$$r = \frac{p_T}{eB_z}$$

$$r[\text{cm}] = \frac{p_T[\text{MeV/c}](10^8 / c)}{B_z[\text{T}]} \approx \frac{p_T}{3B_z}$$

Simple Cuts

- Acceptance of the decay channel in (p_L,p_T)-space should look roughly like this:

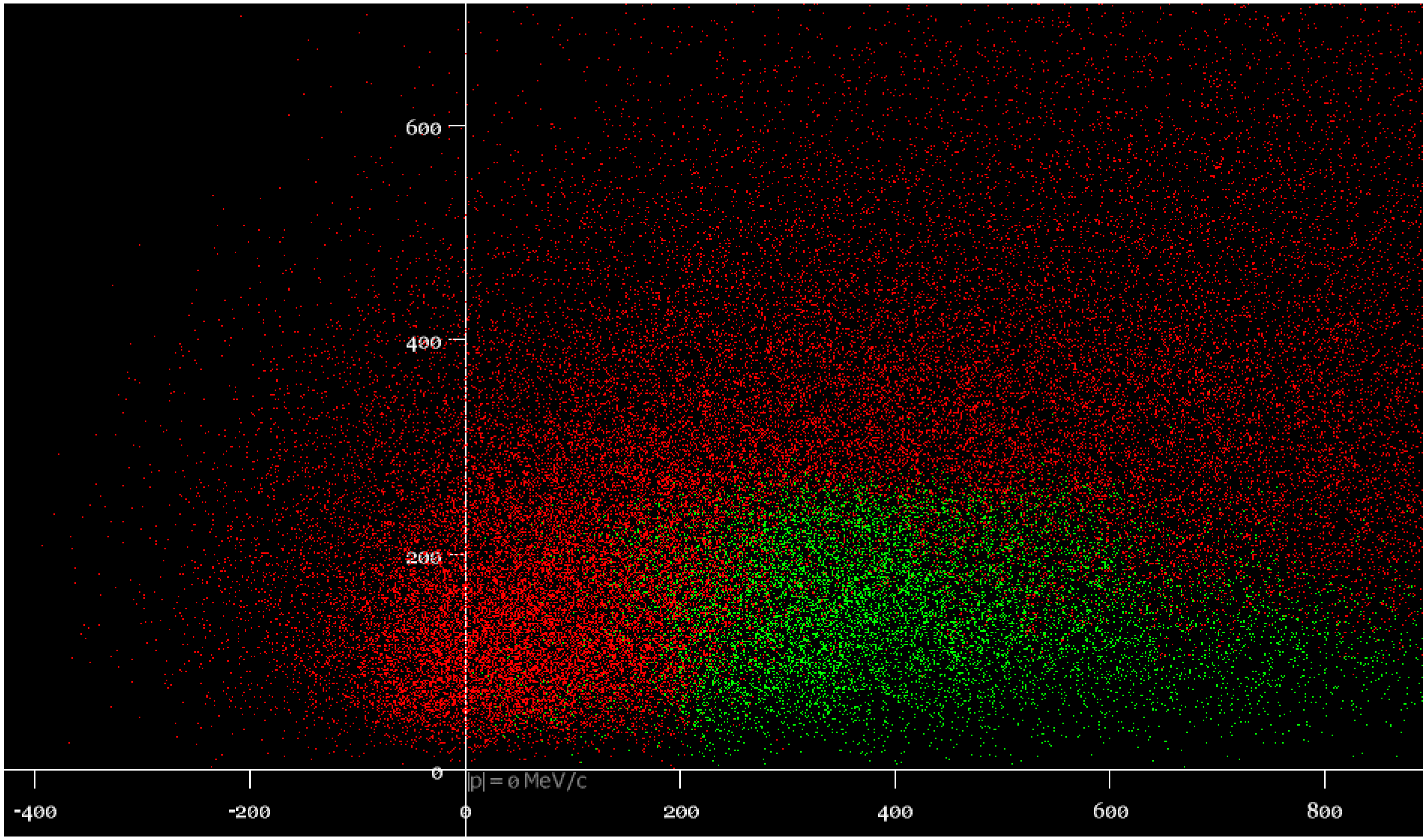


Simple Cuts

- So, does it?
- Pions from one of the MARS datasets were tracked through an example decay channel and plotted by (p_L, p_T)
  - Coloured green if they got the end
  - Red otherwise
- This is not entirely deterministic due to pion → muon decays and finite source

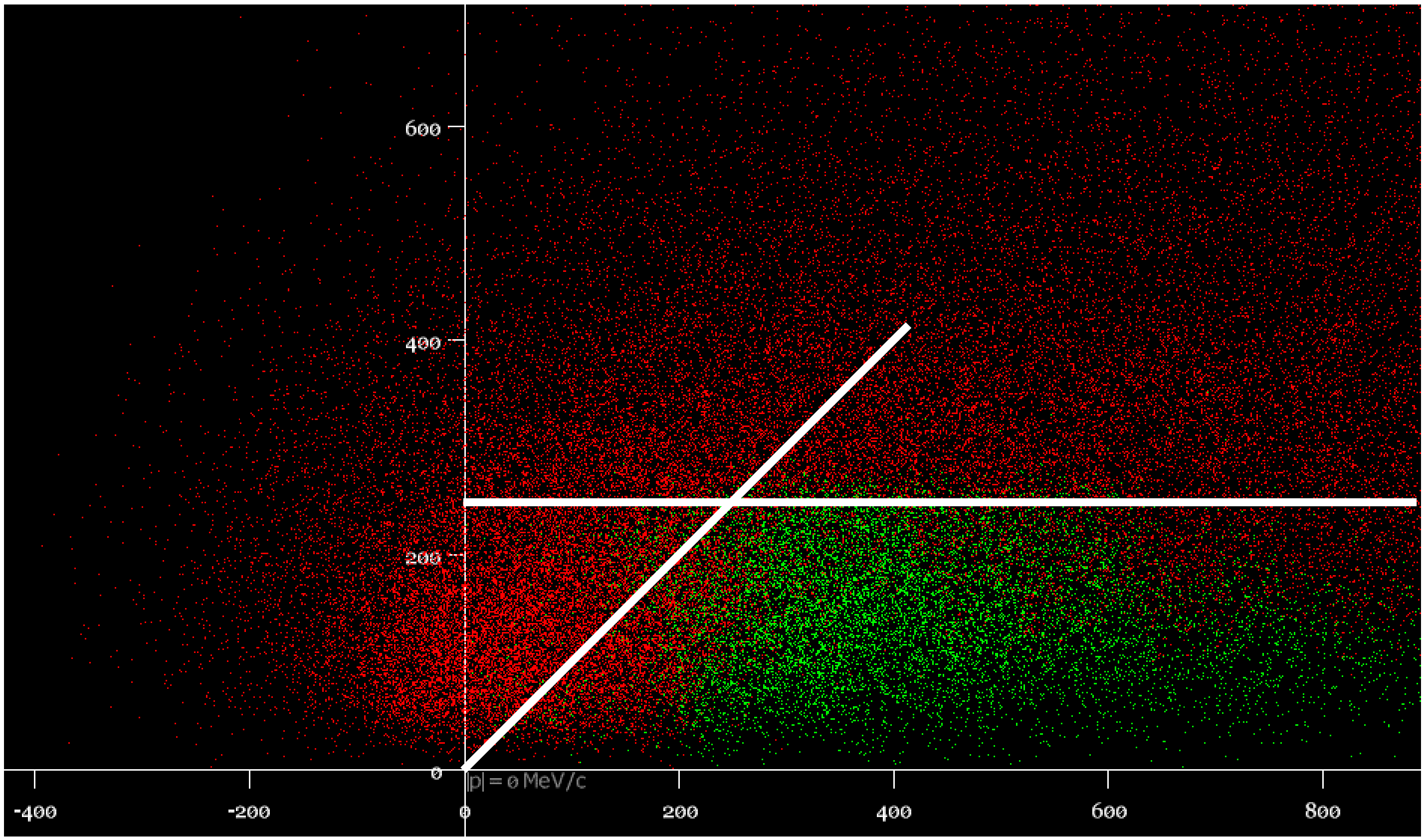
Simple Cuts

- So, does it?



Simple Cuts

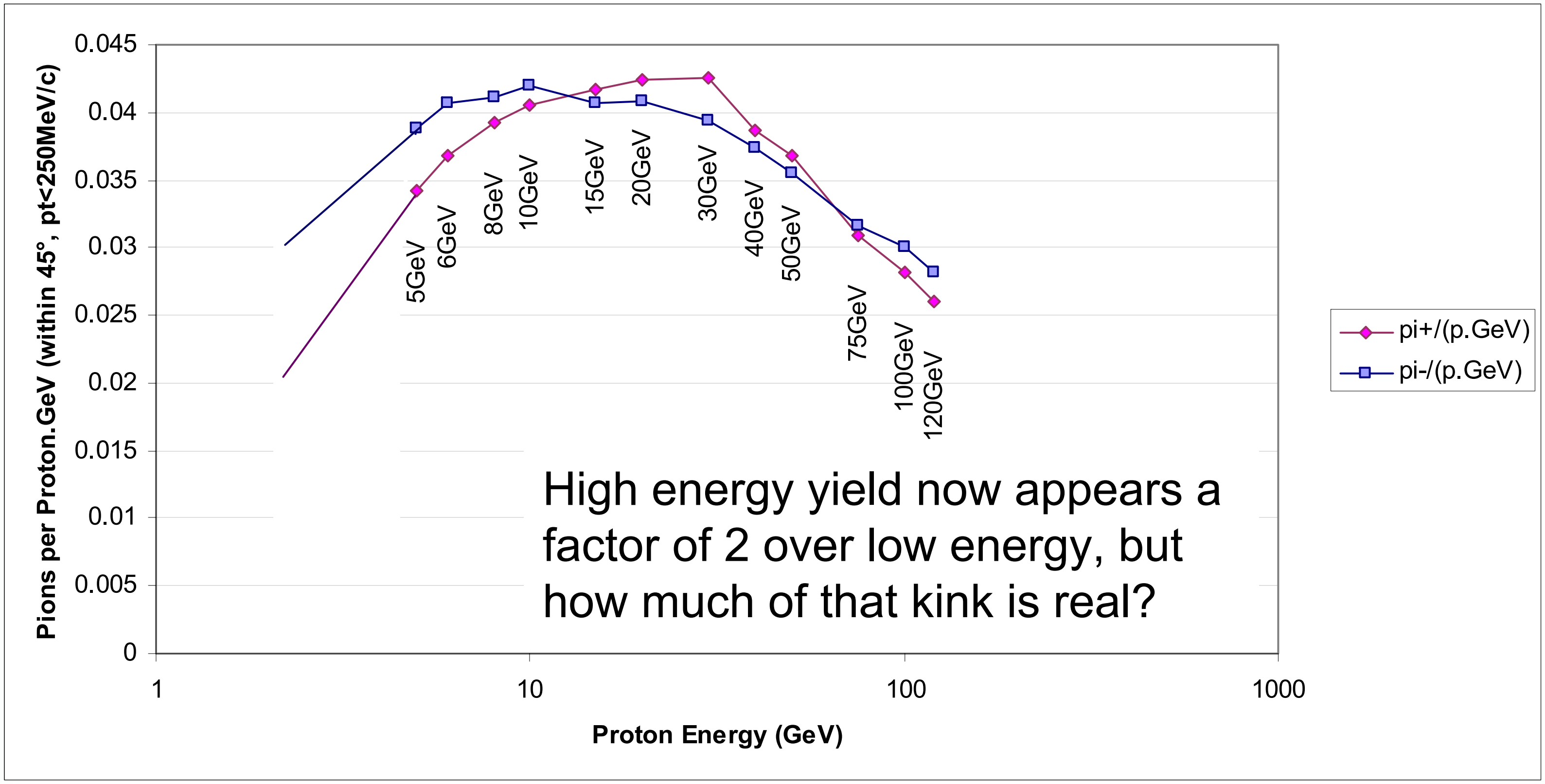
- So, does it? Roughly.



Simple Cuts

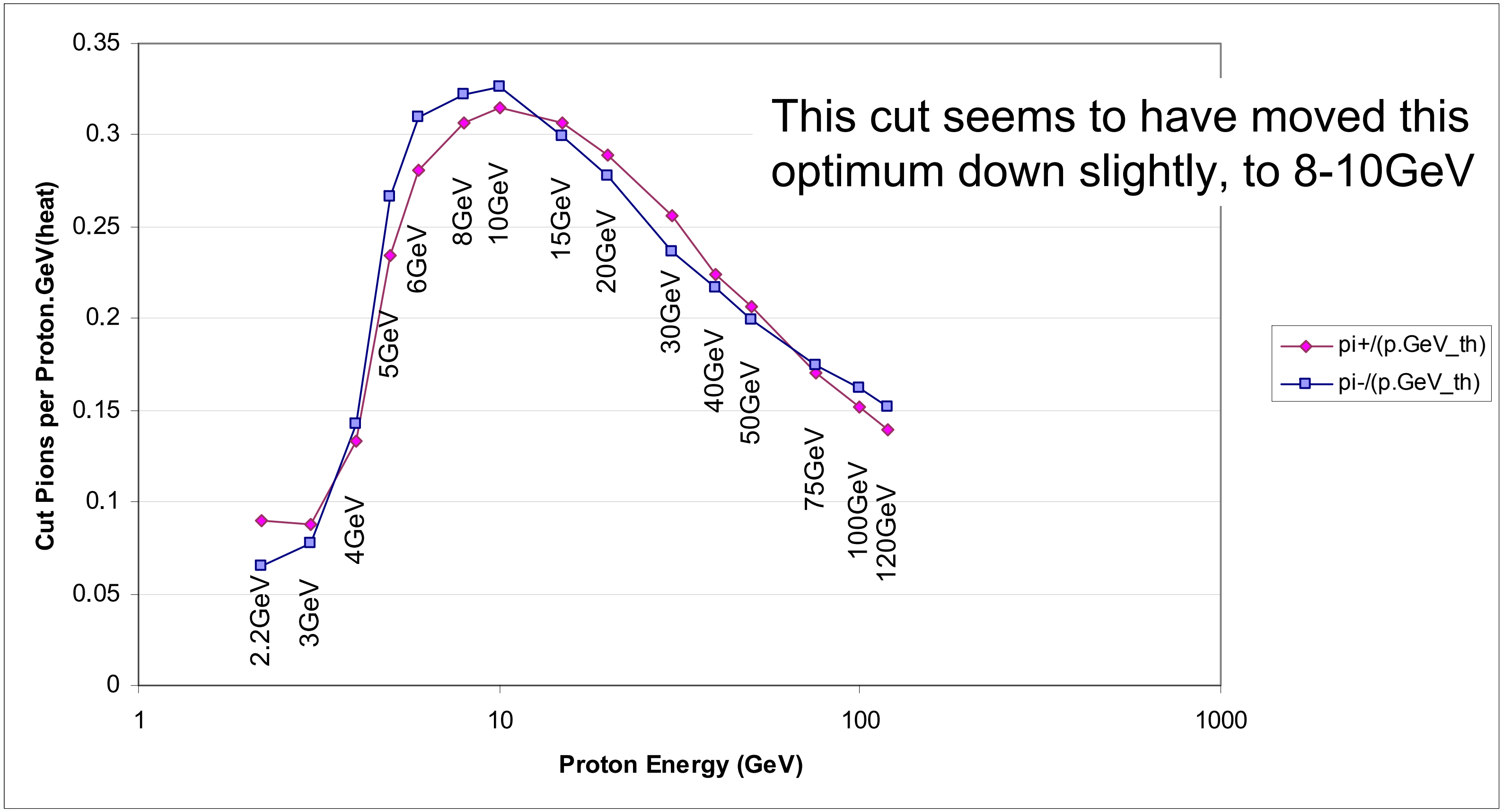
- So, does it? Roughly.
- If we choose:
  - $\theta^{max} = 45°$
  - $p_T^{max} = 250$ MeV/c
- Now we can re-draw the pion yield graphs for this subset of the pions

Cut Yield of π^+ and π^-



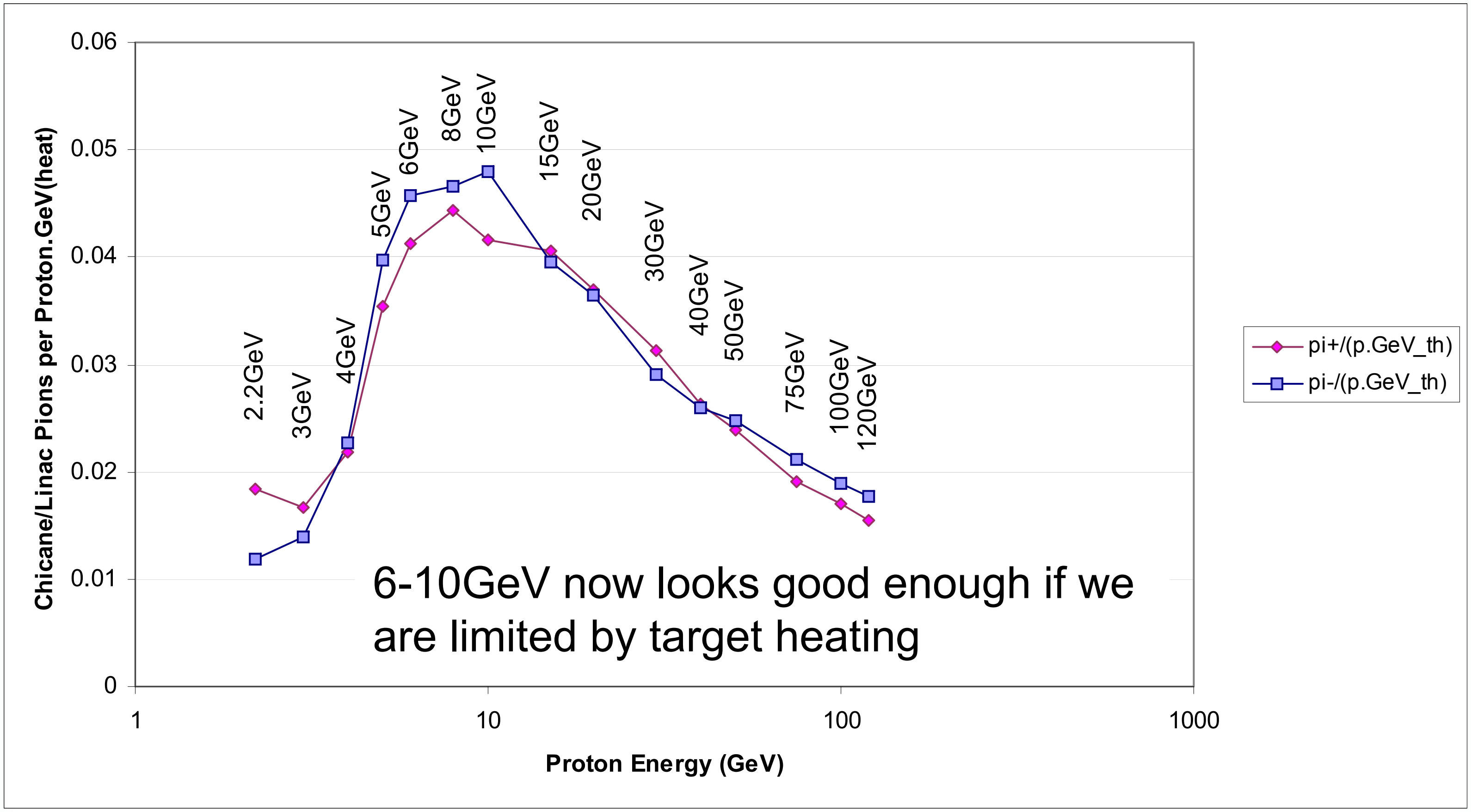
- Normalised to unit beam power (p.GeV)

Cut Yield of π^+ and π^-



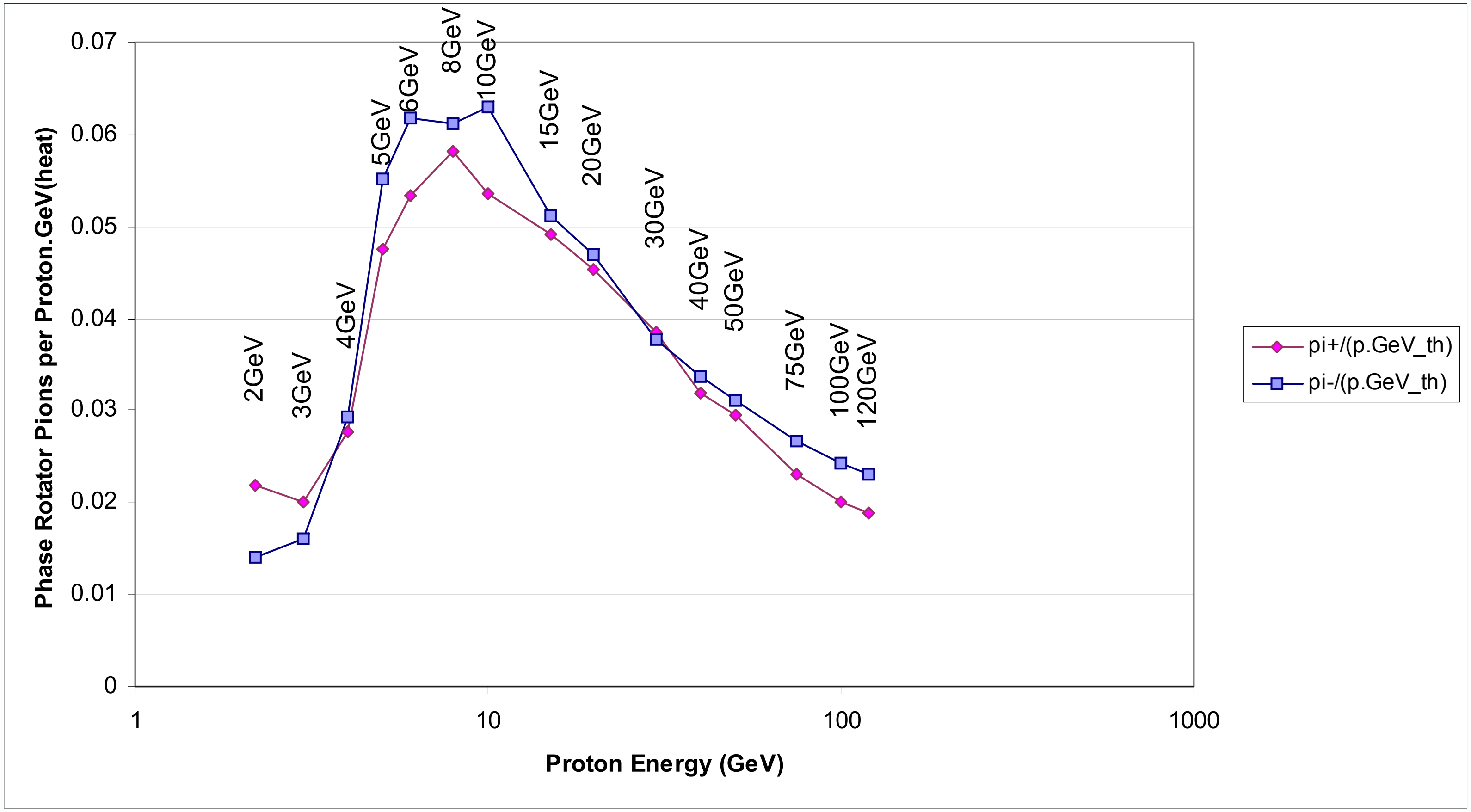
- Normalised to unit rod heating

Chicane/Linac Transmission



- Normalised to unit rod heating

Phase Rotator Transmission

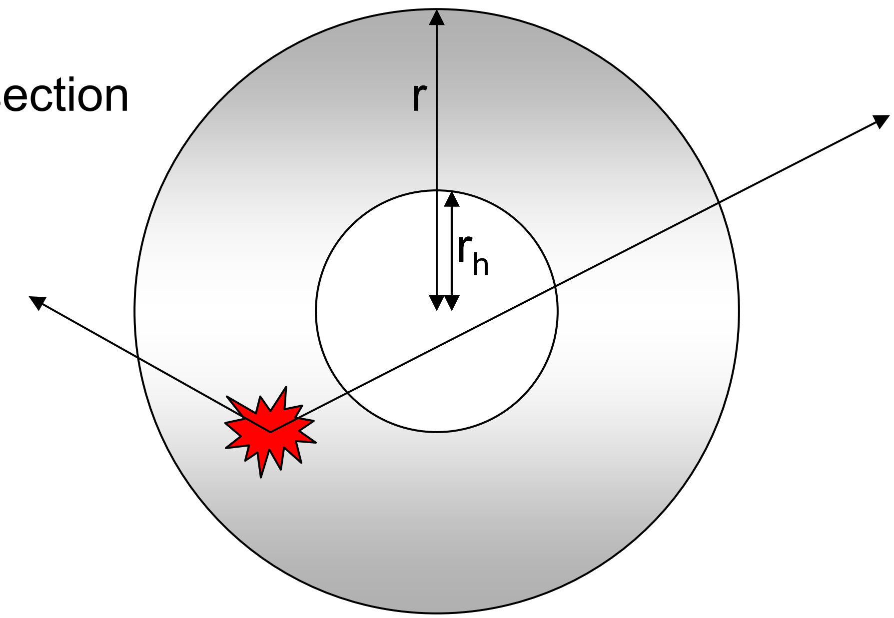


- Normalised to unit rod heating

Rod with a Hole

- Idea: hole still leaves $1-(r_h/r)^2$ of the rod available for pion production but could decrease the path length for reabsorption

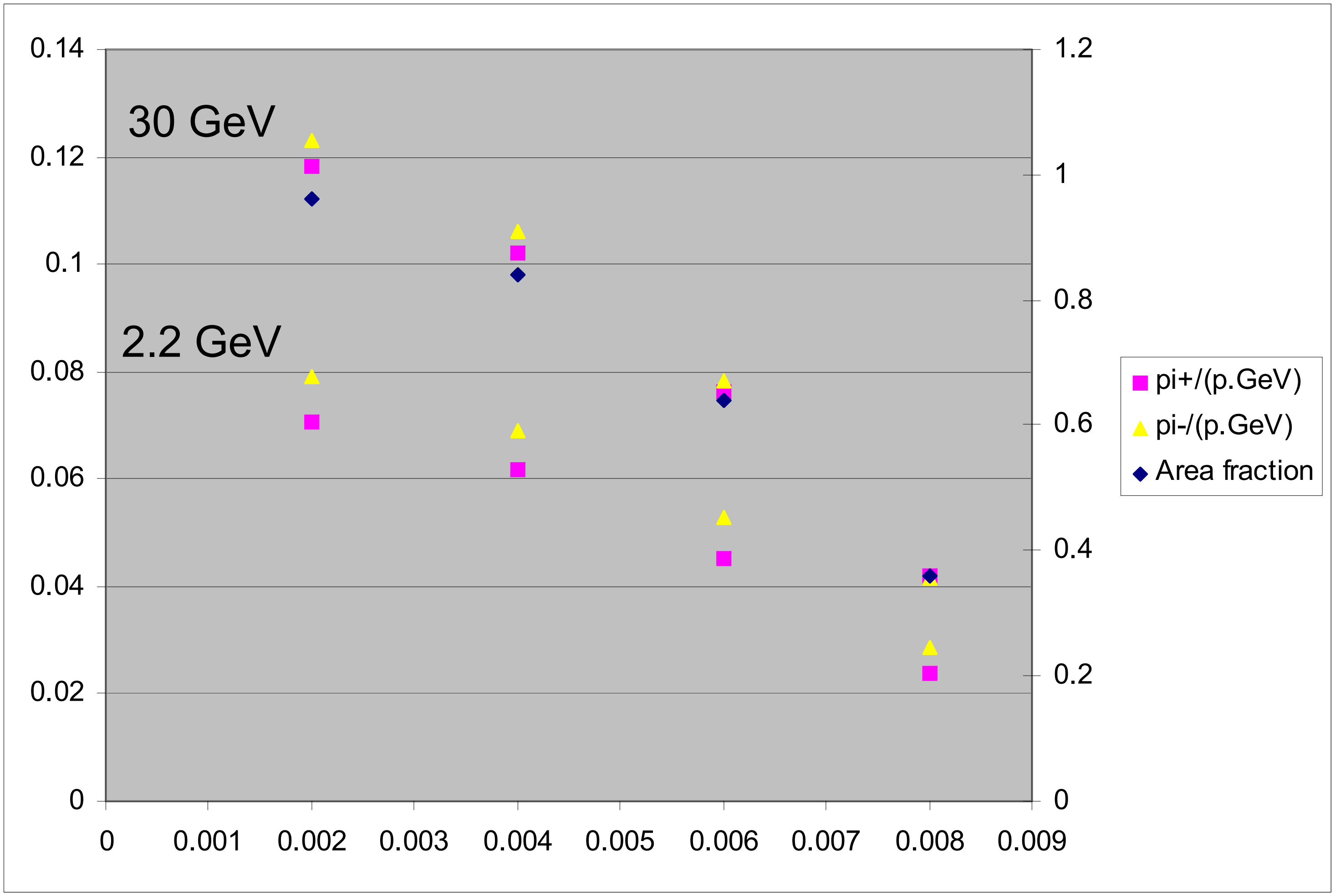
Rod cross-section



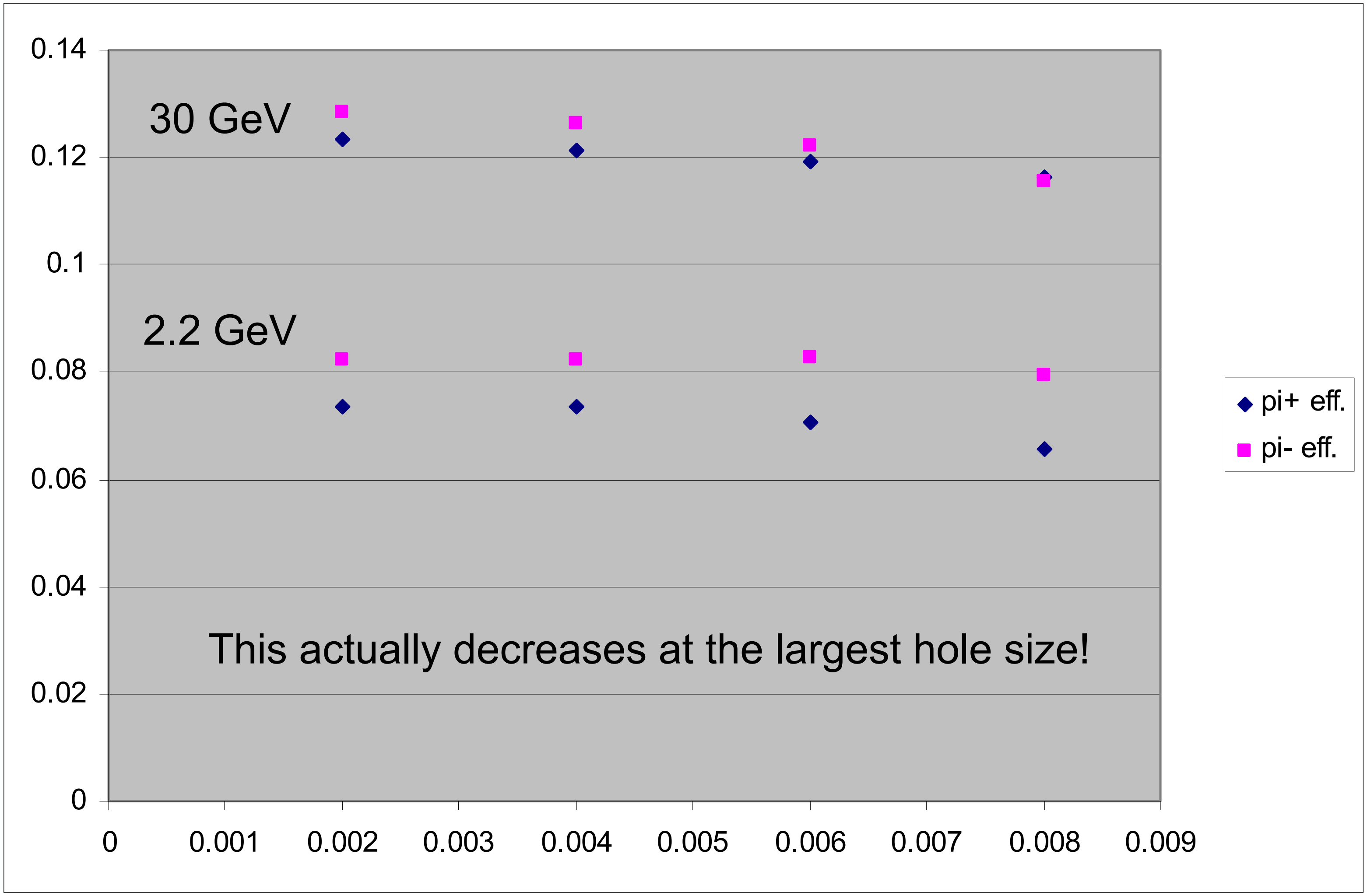
Rod with a Hole

- Idea: hole still leaves $1-(r_h/r)^2$ of the rod available for pion production but could decrease the path length for reabsorption
- Used a uniform beam instead of the parabolic distribution, so the per-area efficiency could be calculated easily
- $r = 1\text{cm}$
- $r_h = 2\text{mm}, 4\text{mm}, 6\text{mm}, 8\text{mm}$

Yield Decreases with Hole



Yield per Rod Area with Hole



Rod with a Hole Summary

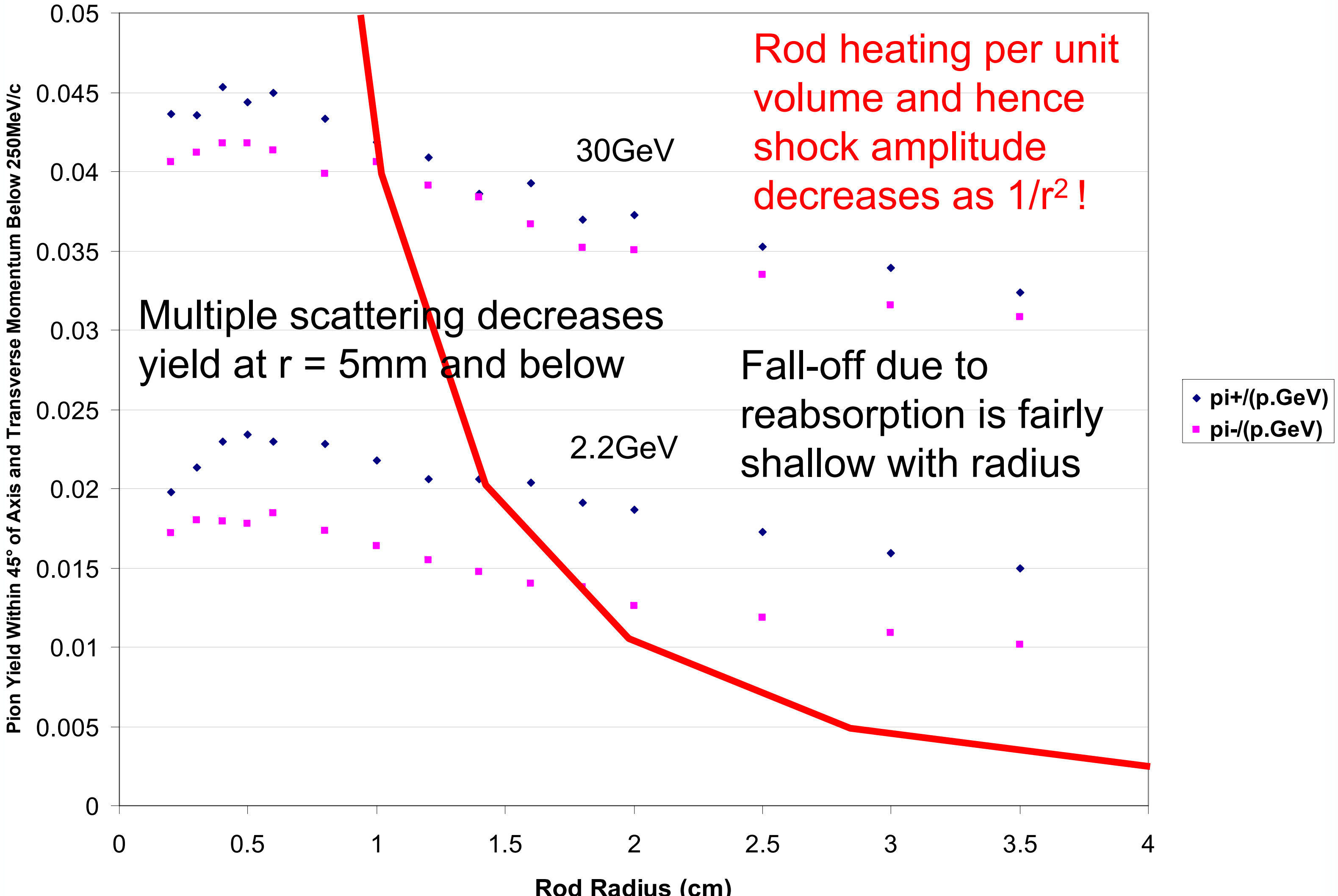
- Clearly boring a hole is not helping, but:
- The relatively flat area-efficiencies suggest reabsorption is not a major factor
  - So what if we increase rod radius?
- The efficiency decrease for a hollow rod suggests that for thin (<2mm) target cross-sectional shapes, multiple scattering of protons in the tantalum is noticeable

Variation of Rod Radius

- We will change the incoming beam size with the rod size and observe the yields
- This is not physical for the smallest rods as a beta focus could not be maintained

Emittance ε_x	Focus radius	Divergence	Focus length
25 mm.mrad extracted from proton machine	10mm	2.5 mrad	4m
	5mm	5 mrad	1m
	2.5mm	10 mrad	25cm
	2mm	12.5 mrad	16cm

Cut Yield with Rod Radius



Future Work

- Resimulating with the LAQGSM added
- Benchmarking of MARS15 results against a GEANT4-based system (K. Walaron)
- Tracking optimisation of front-ends based on higher proton energies (sensitivity?)
- Investigating scenarios with longer rods
  - J. Back (Warwick) also available to look at radioprotection issues and adding **B**-fields using MARS